MONTHLY WEATHER REVIEW

VOLUME 83 NUMBER 10

OCTOBER 1955

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U. S. DEPARTMENT OF COMMERCE • WEATHER BUREAU

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As the national meteorological service for the United States, the Weather Bureau issues several periodicals, serials, and miscellaneous publications on weather, climate, and meteorological science as required to carry out its public service functions. The principal periodicals and serials are described on this page and on the inside of the back cover. A more complete listing of Weather Bureau publications is available upon request to Chief, U. S. Weather Bureau, Washington 25, D. C.

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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: $3.00; additional for foreign mailing, $1.00; 30¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

The printing of this publication has been approved by the Director of the Bureau of the Budget, February 9, 1955.

DEPARTMENT OF COMMERCE
SINCLAIR WEEKS, Secretary

WEATHER BUREAU
F. W. REICHELDERFER, Chief

MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

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METEOROLOGICAL TREND AND THE APPARENT RISE IN SEA LEVEL ALONG THE SOUTH CAROLINA COAST

EUGENE J. DE VEAUX

U. S. Weather Bureau, Charleston, S. C.

[Manuscript received July 15, 1954; revised September 13, 1955]

ABSTRACT

The height of the level of the sea at any time, exclusive of the astronomical tide, is closely related to the atmospheric pressure and the prevailing wind. Where the gaging station is situated on a tidal river the precipitation over the drainage basin may also be an influence. Important secular trends of these three elements are noted during the history of the tide gage at Charleston, S. C. The progressive rise in sea level as indicated by this gage may have been influenced by these trends.

1. INTRODUCTION

In the 22-year period from 1926 through 1948, sea level has apparently increased by 0.8 foot at Charleston, S. C. If this rise were to continue for the next 30 or 40 years Charleston would have to be diked to keep the sea water out, for much of the peninsula upon which the city is built lies just at the higher high tide level. However, during the years 1949 and 1950 the computed sea level indicates an abrupt drop of almost 0.4 foot. From 1950 through 1954 there has been little change.

Much popular apprehension has resulted from this rather alarming rise. The explanations of the rise, since it is a relative question between land and sea, have resolved into two hypotheses: (a) an increased supply of water along the coast, (b) a subsidence of the land mass. These hypotheses, considered either separately or in conjunction, have not been accepted as conclusive [1].

The extensive and rapid fluctuation in the level of the sea (up 0.4 ft. and down 0.4 ft.) at Charleston during the 5-year period from 1945 to 1950 strongly suggests the weather as the cause. A substantial change in the frequency of the wind from effective directions may possibly be of importance here, as well as the underlying influence of the general trend since 1926. For it should not be ignored, in accepting a rate of rise, that measurements of sea level obtained from gages along the upper portion of the Continental Shelf are affected by important meteorological elements [2]. Yearly variations of the sea that depart from the general trend are attributed to the disturbing effects of wind and weather which are not repeated exactly [3]. In this paper it is desired to present some limited evidence that a portion of the total rise may be traced to the effects of secular trends in wind, precipitation, and pressure.

2. EFFECTS OF METEOROLOGICAL ELEMENTS

WIND

Figure 1 shows the location of the Coast and Geodetic Survey tide gage and the Weather Bureau station at Charleston, S. C., from which the data appearing herein were obtained. The tide gage is a standard automatic type furnishing a continuous trace of the water level. It

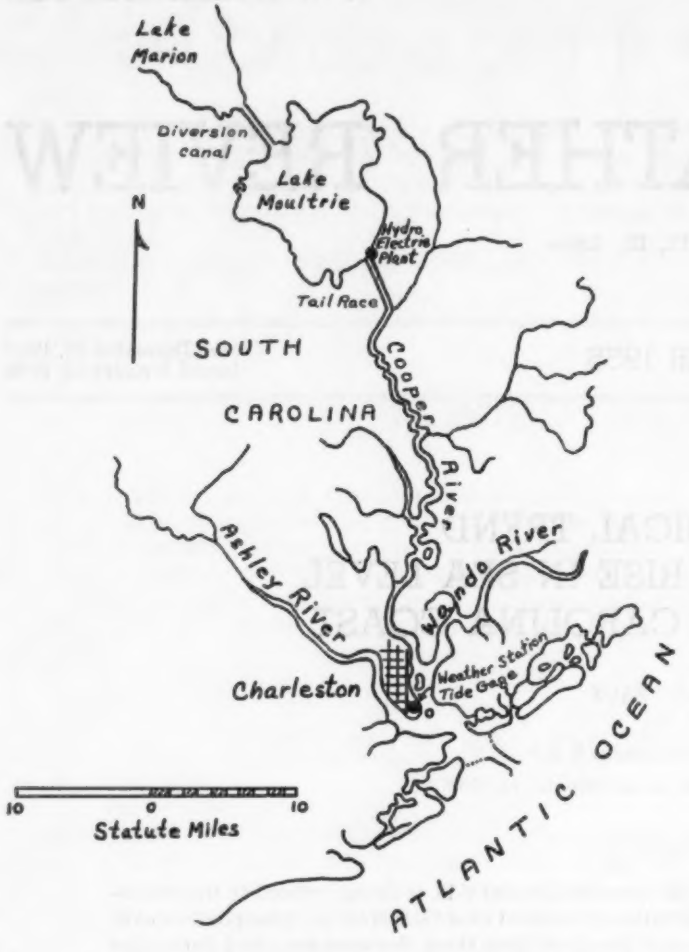

Figure 1.—Location of tide gage and weather station in relation to harbor at Charleston, S. C.

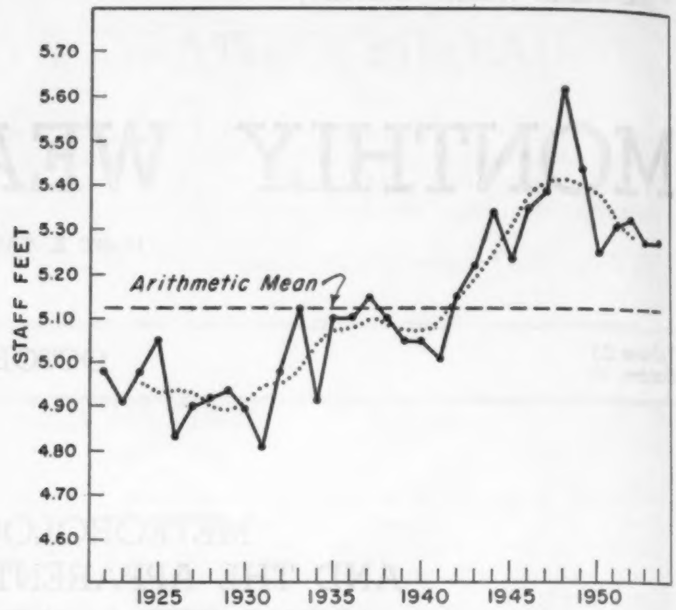

Figure 2.—Annual mean sea level (solid line) and moving 5-year averages (dotted line) at Charleston, S. C. over period of record. (Heights are referred to zero of the tide staff.) Note: Tide planes for Charleston are based on gage records for the 19-year period 1924–1942. Mean low water for this period corresponds to a reading of 2.3 feet on the staff of 1921. Gage heights are referred to the staff of 1921 and can therefore be referred to mean low water by subtracting 2.3 feet. The mean low water to which predicted heights refer is determined with relation to mean sea level. This relation is 2.7 feet at Charleston. Referred to a fixed datum the height of mean low water is affected by changes in sea level so that observed heights when referred to mean low water will depend on which particular years are used as a basis of mean low water determination. (This information has been kindly furnished by the Coast and Geodetic Survey, Washington, D. C.)

is situated about six miles from the open sea, on the edge of a deep channel, in a spacious harbor, into which empty three main streams: the Ashley, the Cooper, and the Wando Rivers—none of which have extensive drainage basins. In 1942 a hydroelectric plant began diverting Santee River water into the Cooper River through turbines. No bypass is released into this stream.

The weather station has been in continuous operation at this same location since 1897. The tide gage, located only a few hundred yards away, was established in 1921. The year 1922 is the first complete year of tide record. The height of the wind vane, which is 92 feet above the ground, and its location have remained unchanged since its installation. The city has had no room for expansion in the vicinity of the station, and neither tall buildings nor obstructions have interfered with the entire record. The exposure is considered excellent. The record is autographic on multiple register for wind and precipitation.

Figure 2 indicates graphically the annual mean sea level at this city. The moving 5-year averages show the general trend, eliminating the up and down changes from year to year. The significant rise from 1945 through 1948 and the abrupt fall from 1948 through 1950 are evident. This short-period fluctuation of almost 0.4 foot must be caused by wind and weather or by the operation of the hydroelectric plant. Mayport, Fla., exhibits a graph of mean sea level similar to Charleston's [1] during this period and it appears unlikely that the fluctuation can be attributed to the plant. Zetler [1] has ascribed a rise of 0.09 foot at Charleston to this diversion since 1942 and has shown the large reduction in salinity.

Any explanation of the rise involving the elements of wind and pressure should not be restricted to the harbor alone. While some minor influence must occur within its confines, tbe major influence is produced over the ocean and on the upper limits of the Continental Shelf. The more noticeable daily variations can be observed on the outer beaches and waterways not closely connected with the harbor.

It is commonly supposed by those who live along the coast that a wind blowing toward the shore raises the level of the sea while a wind blowing from the shore lowers it.

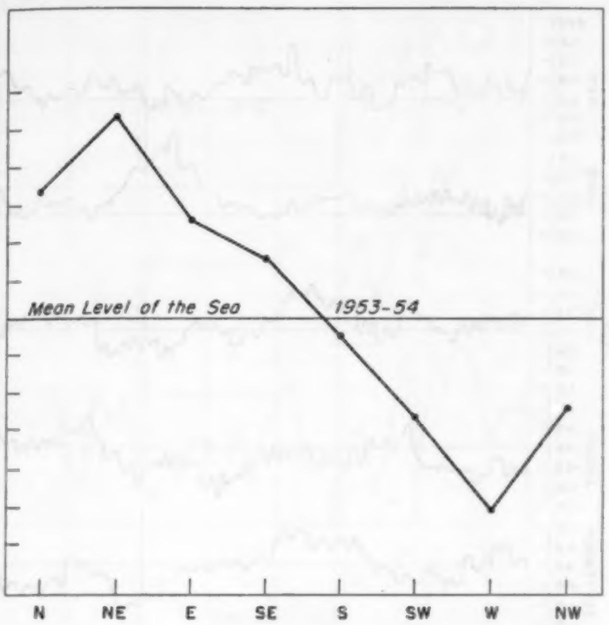

Figure 3.—Departure from the mean level of the sea, Charleston, S. C., 1953–1954, with persistent (6 hours or more) winds from the principal directions for the same period.

A more careful study will show that this is not entirely true, for the coastline from Cape Hatteras, N. C., to Savannah, Ga., extends northeast-southwest and yet a prevailing north wind at Charleston will be accompanied by considerable rise while there is little change with a south wind. To explain these effects of the wind on the water level, it may be said briefly that the wind through friction generates a current of ocean water that is forced upward on the Continental Shelf and impinges on the coastal slope [4]. These currents depend on the direction, duration, fetch, and force of the wind. The local wind may not always be representative of the condition producing the variation in the sea. In addition, the currents as a general rule move or set to the right of the wind flow. Specific measurements of wind-driven currents have been made at the lightships along the Atlantic Coast [5].

Figure 3 shows the average variations in the sea expressed as the deviation from the mean level of the sea (observed less predicted tides) that have occurred at the Charleston station during the period 1953–1954 with the wind at each of the cardinal and intercardinal points. In determining these values, only winds of persistent direction for 6 hours or more were used. At the end of at least 6 hours persistency the actual successive high and low tides were compared with the predicted tides for the same time and the differences noted. These residuals were averaged for each direction and plotted in the graph. Continuous readings of high and low water were used as long as the wind direction did not vary. It should not be assumed that the extent of the variations for every year of record would have the same values. But it can be assumed that the north, northeast, and east winds

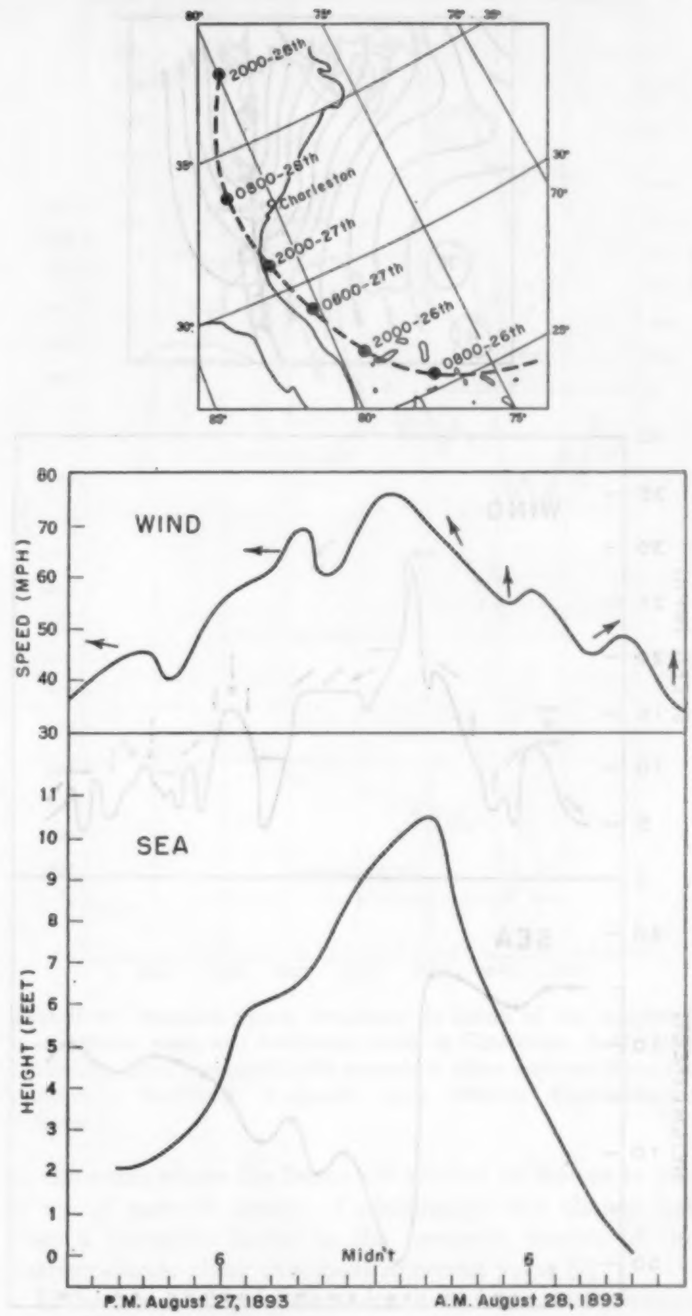

Figure 4.—Effect of hurricane of August 27–28, 1893, on the level of the sea at Charleston, S. C. The curve of sea height shows the approximate variation due to wind and pressure, the predicted tides having been removed. (Based on graph by E. P. Alexander, *Monthly Weather Review*, May 1896.) The map shows the track of the hurricane from August 26–28. (*Monthly Weather Review*, August 1893.)

produced higher water levels and that the southwest, west, and northwest winds produced lower water levels throughout the record. In this study the directions are grouped into those that produce obvious rises and those that produce obvious falls in the level of the sea: N-NE-E and SW-W-NW. The average departures accompanying

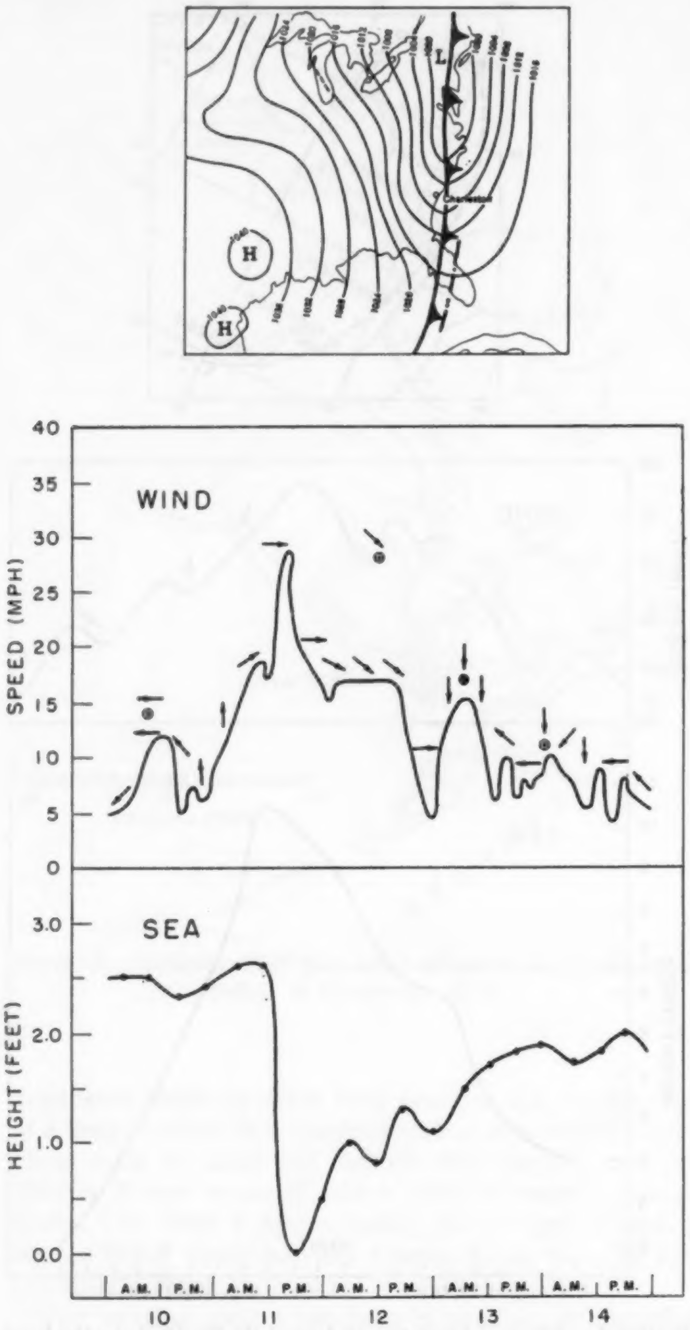

FIGURE 5.—Variation in the level of the sea (predicted tides removed) at Charleston, S. C., February 10–14, 1955, with strong westerly winds following a frontal passage. In wind graph arrows indicate direction according to the usual convention; circled dot below arrow indicates fastest full mile. Weather situation is shown by the map for 1:30 p. m. EST, February 11, 1955.

the southeast and south winds are small. Consideration will not be made of these two directions in the development of the discussion.

The extent of the elevation or depression of the sea (predicted less observed tides) at Charleston may be from about 8 to 10 feet above the height of the predicted tide during the most violent hurricane to about 3 feet below

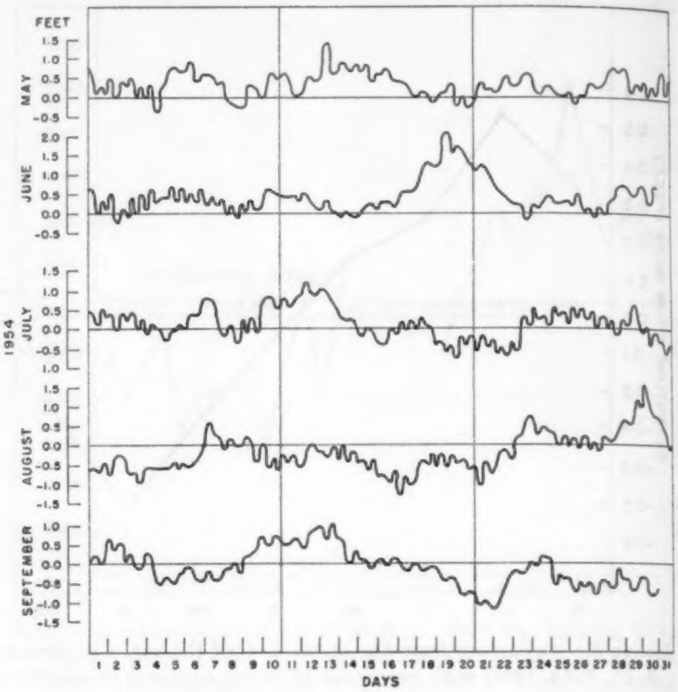

FIGURE 6.—Continuous variation in the level of the sea at Charleston, S. C., May through September 1954. Departures are based on sea level for 1954 and are the differences between the actual and predicted tides. The departures may be attributed to disturbing meteorological effects.

with intense westerlies. An analysis of the hurricane of August 27–28, 1893, as it affected the water level at Charleston is presented in figure 4. The predicted tides occurring during the hurricane have been removed. The remaining effect may be attributed to the storm for the purpose of giving a fair idea of what the wind and pressure can do. In figure 5 the influence of some strong westerlies on the level of the sea following a frontal passage is represented.

In defining sea level, it is sufficient here to say that mean sea level is the average of the tabulated hourly heights of the tide and includes changes brought about by meteorological causes [3]. That these changes due to the weather are considerable and continuous may be noted in figure 6. In deriving the curve for this figure the actual heights at time of high and low water were compared with the predicted heights as they appear in the tide tables for this port. The predicted heights of the tide were referred to mean low water for that particular year and are based on the astronomical tides adjusted to the "normal" seasonal effects of wind and weather [2]. The difference between these two values is a reasonable estimate of the extent of the effect on the sea of the wind and weather prevailing at the time of the measurement.

In figure 7, the relative frequency in hours of the combined north, northeast, and east winds each year from 1918 through 1954 has been graphed. Records for several other stations along the Atlantic Seaboard were investi-

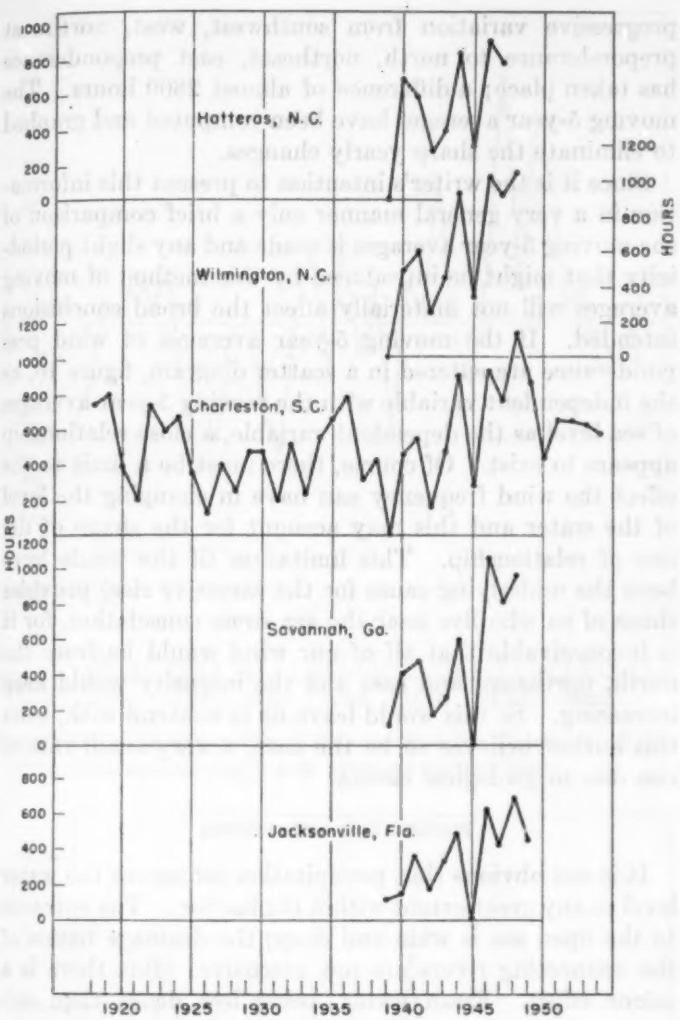

Figure 7.—Relative yearly frequency in hours of the combined north, northeast, and east winds at Charleston, S. C., 1918 through 1954, compared with records at other Atlantic Seaboard stations. Prepared from Station Climatological Record.

gated and also appear in the figure. The comparison appears to assure that the increase of these winds was not just a local phenomenon. The frequency of this group of combined winds for Charleston increased by almost 1200 hours from 1939 through 1948 and was still in 1954 approximately 400 hours in excess of the amount in 1926.

In figure 8, the relative frequency in hours of the combined southwest, west, and northwest winds is shown from 1918 through 1954 for Charleston and a portion of the record for the same stations as in figure 7. From 1926 through 1948 there has been a reduction of these winds of over 1600 hours at Charleston. Here too, the other stations are in general agreement. A pronounced similarity of change has occurred from Charleston northward to Hatteras, N. C. At Savannah, Ga., a sharp reduction is recorded after 1945 that is evidently caused by the station being moved to the airport.

This variation in the wind frequency is no minor change and must have significance also over the ocean adjacent

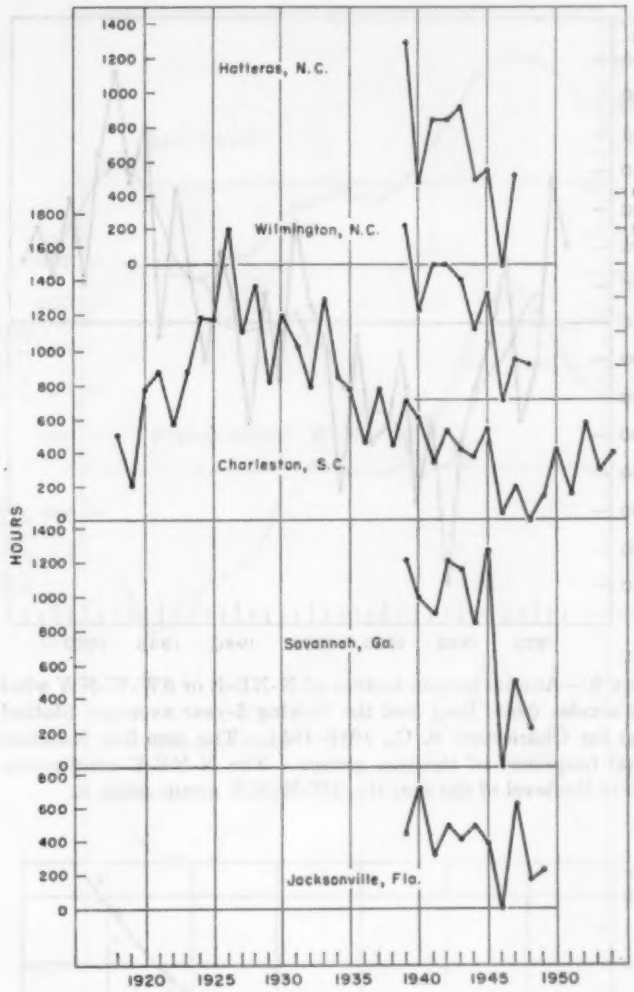

Figure 8.—Relative yearly frequency in hours of the combined southwest, west, and northwest winds at Charleston, S. C., 1918 through 1954, compared with records at other stations along the Atlantic Seaboard. Prepared from Station Climatological Record.

to the coast where the forces are applied to the sea to pile it up or move it away. Undoubtedly this change has been a causative factor in the excessive erosion of the barrier islands along this coast in recent years [6].

If the meteorological elements that have some influence on the level of the sea were consistent, a relation between them and the rise of the sea would be remote. But it is difficult to ignore these important trends, particularly as they are related to the pattern of rise, and since they have not been repeated during the record of the gage.

In figure 9, a graph is presented to show the preponderance of these groups of combined winds (N-NE-E and SW-W-NW) as they have occurred from 1918 through 1954 at Charleston. The zero line indicates equal frequency of the two groups. That is, if the combined north, northeast, and east winds were equal to the combined southwest, west, and northwest winds for any year, the point would fall upon the zero line. That portion of the graph below the zero line indicates a preponderance, or

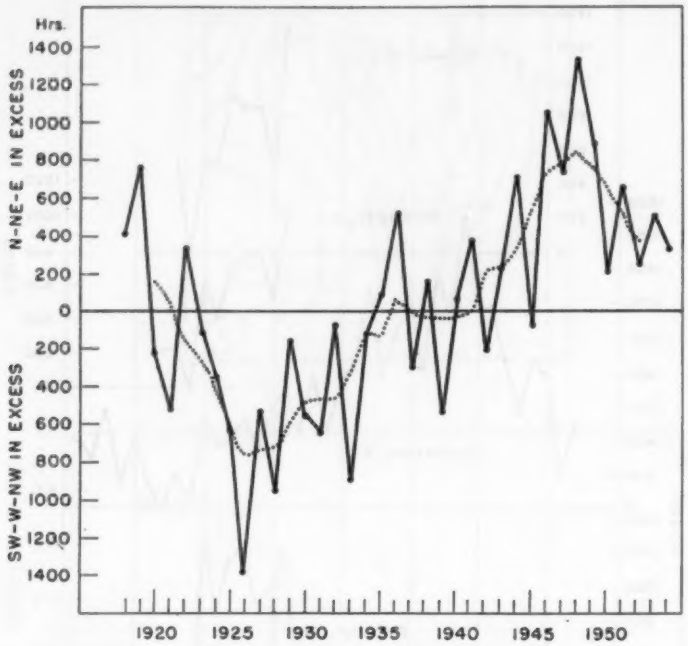

FIGURE 9.—Annual preponderance of N-NE-E or SW-W-NW wind frequencies (solid line) and the moving 5-year averages (dotted line) for Charleston, S. C., 1918–1954. The zero line indicates equal frequency of the two groups. The N-NE-E wind group lowers the level of the sea; the SW-W-NW group raises it.

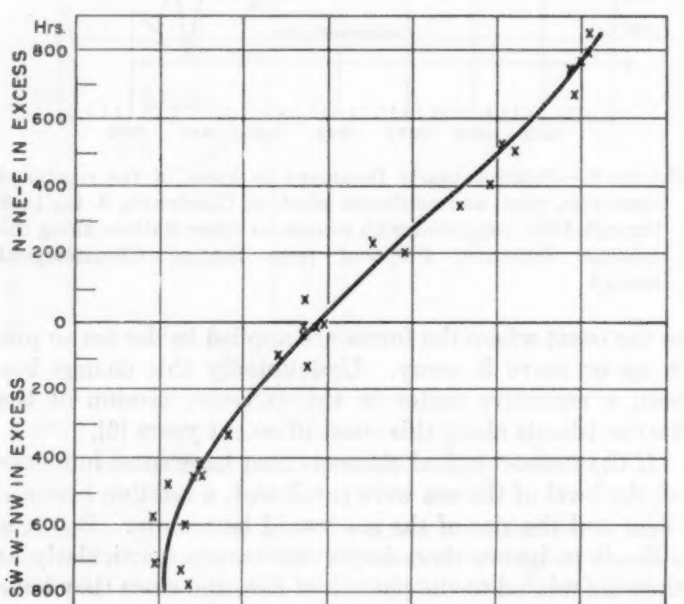

FIGURE 10.—Relationship between 5-year moving averages of wind preponderance and 5-year moving averages of level of the sea, Charleston, S. C., 1922–1954. (Heights are referred to zero of tide staff.)

excess of one group over the other, of winds that lower the sea; and that portion above, a preponderance of those winds that raise the sea. From 1926 through 1948 a progressive variation from southwest, west, northwest preponderance to north, northeast, east preponderance has taken place; a difference of almost 2800 hours. The moving 5-year averages have been computed and graphed to eliminate the sharp yearly changes.

Since it is the writer's intention to present this information in a very general manner only a brief comparison of the moving 5-year averages is made and any slight periodicity that might be introduced by this method of moving averages will not materially affect the broad conclusions intended. If the moving 5-year averages of wind preponderance are entered in a scatter diagram, figure 10, as the independent variable with the moving 5-year averages of sea level as the dependent variable, a close relationship appears to exist. Of course, there must be a limit to the effect the wind frequency can have in changing the level of the water and this may account for the shape of the line of relationship. This limitation (if the winds have been the underlying cause for the excessive rise) provides those of us who live near the sea some consolation, for it is inconceivable that all of our wind would be from the north, northeast, and east and the intensity would keep increasing. So this would leave us to contend with, what this author believes to be the case, a very small rate of rise due to geological causes.

PRECIPITATION AND PRESSURE

It is not obvious that precipitation influences the water level to any great extent within the harbor. The entrance to the open sea is wide and deep; the drainage basins of the connecting rivers are not extensive. But there is a minor effect. Fresh water, being less dense than salt water, will tend to remain in the upper layers "floating" on the more dense salt layers. The coastal plain is flat. There is not much head to the water in the upper reaches of the rivers flowing into the harbor; consequently drainage to the sea is sluggish. Figure 11 shows the yearly precipitation for Charleston and the moving 5-year averages show the trend for the period. The change has been from deficiencies during the period of low sea level to excesses during the period of high sea level. After the year 1947 rainfall began to decline but regulated operation of the hydroelectric plant has continued the flow of less dense water by the gage [1].

The average pressure distribution over the surface of the earth is not equal. Wherever contrasts of high and low pressure exist over the seas the water is depressed under the higher pressure and elevated under the lower. The extent of the movement is masked in shallow water by the effect of the wind which is a function of the pressure gradient. For a stable sea level it would be required that this normal oceanic distribution of pressure not change; or that the continuous changes fluctuate consistently. This would not be expected to occur in the change from glacial to inter-glacial periods, or in the shorter-period climatic and secular fluctuations which are characteristic of, but not as extreme in degree as, the geological [7] [8] [9].

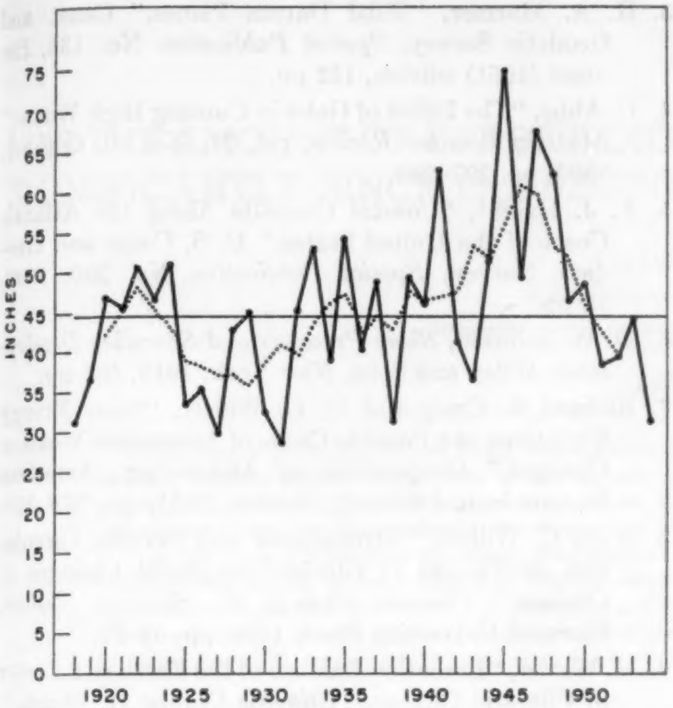

FIGURE 11.—Yearly precipitation (solid line) for Charleston, S. C., 1918–1954, and moving 5-year averages (dotted line).

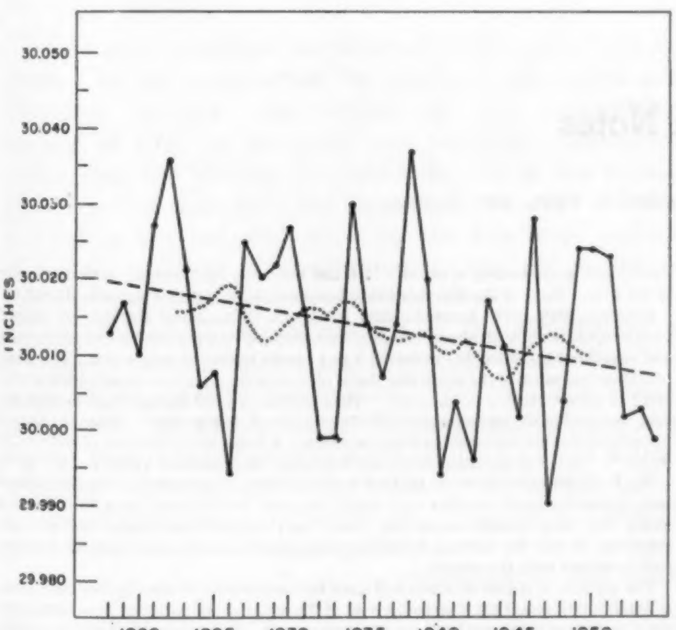

FIGURE 12.—Annual mean station pressure (solid line) at Charleston, S. C., 1918–1954, and the 10-year moving averages (dotted line). Assigned station elevation is 48 ft.

The annual mean station pressure and the moving 10-year averages at Charleston appear in figure 12. The trend has been for lower pressure since the establishment of the tide gage. The change has been very slight but possibly significant in a secular or climatic change.

To sum up the separate trends, figure 13 shows by means

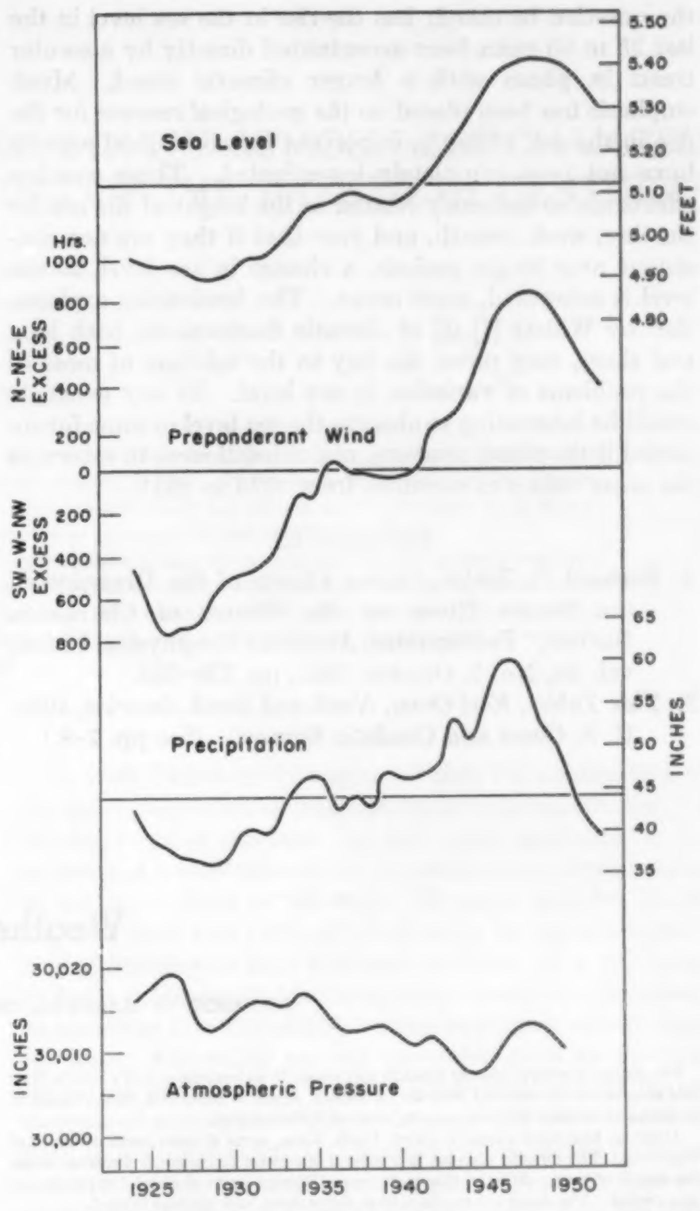

FIGURE 13.—Trend of sea level, wind preponderance, precipitation, and pressure at Charleston, S. C., 1923–1954, taken from moving averages presented in preceding graphs.

of the moving averages the sea level and the meteorological elements as presented in the previous graphs.

3. CONCLUSION

This paper is restricted to local material available to the author and is not intended as a general hypothesis based upon such limited data. There have been changes in the sea level elsewhere than the South Carolina Coast. Some Alaskan stations have recorded a fall in the sea, or a rise in the land, or just the effects of the wind and weather on the water, or perhaps all three. The sea along the Gulf Coast has shown an extensive change. No attempt has been made to apply the reasoning presented here to other sections. However, it is intended in this paper that

the question be asked: has the rise in the sea level in the last 25 to 30 years been accentuated directly by a secular trend in phase with a longer climatic trend. Much emphasis has been placed on the geological reasons for the rise in the sea while the important meteorological aspects have not been completely investigated. These weather effects are so definitely related to the height of the sea for the day, week, month, and year that if they are not consistent over longer periods, a change in sea level, as sea level is computed, must occur. The fascinating explanation by Willett [7] [8] of climatic fluctuations, both long and short, may prove the key to the solution of most of the problems of variation in sea level. In any event, it would be interesting to observe the sea level in some future period if the wind, pressure, and rainfall were to return to the same values as occurred from 1926 to 1931.

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Weather Notes

TORNADOES OF BLACKWELL, OKLA.-UDALL, KANS., MAY 25, 1955

The climax of several days of tornadic and severe thunderstorm activity late in May 1955 occurred on the night of May 25. A tornado struck at Blackwell, Okla., killing 20 persons and injuring 250 with property damage in the millions.

About an hour later a tornado struck Udall, Kans., some 40 miles north-northeast of Blackwell. The tornado traveled in a general southwest to northeast direction across the center of town. Most of this south-central Kansas town of about 750 population was leveled. The death toll stands at 80 at this writing, and 250 were injured.

The purpose of this note is to present some personal observations reported to the authors by several eyewitnesses of these disasters.

Braman, Okla.—On the morning of May 25, Mr. H. M. Fox, a farmer who lives 6 miles west and 1 mile south of Braman, Okla. (see fig. 1 for locations), observed an unusual wind storm. His account follows: "The first that I noticed the storm was about 8:30 a. m., and the appearance was of a dense thunderstorm with possible hail. About 8:45 a. m. we had a very strong wind practically out of the south with a little variation to the east. I would estimate this wind at about 70 to 80 miles per hour. What struck me peculiar at the time was that there were no gusts. It was a straight and continuous wind for approximately 15 minutes. This strip of wind in width was probably 2 miles wide. It blew roofs off buildings, tore down steel buildings, TV towers and anything else that wasn't really fastened down. Immediately after the wind let up, we were out surveying the damage and we noticed that the wind would be light and variable and run from cool to hot. During the storm and immediately following, we had no hail and very little rain, probably 0.04 during the storm and afterward. Going on west from my farm, the next 2 or 3 miles had wind but no damage was noticeable. In the next 3 miles (a strip running north and south) there was also heavy damage. Then we had another strip of about 3 miles where there was no apparent damage. Right east of Caldwell, Kans., there was another strip of perhaps 2 or 3 miles that was heavily damaged. That afternoon beginning at 12 o'clock preceding the tornado at Blackwell that night, the skies were of broken clouds and the wind alternated from hot to cold for several hours."

Tonkawa, Okla.—Mrs. Robert C. Walker reported seeing the funnel of a tornado located about one mile east of Tonkawa. Mrs. Walker had a microbarograph in operation at the time. When the tornado was sighted east of town, the barogram showed a sharp fall of about 0.08 inch Hg followed by a sharp rise of about 0.10 inch Hg. (The minimum pressure was recorded at about 2055 CST, however there was no time check with which to determine the accuracy of the time element.) Shortly after 2100 CST the "worst hail in the history of our city" fell but with only light winds. Hail was heavier to the west. Some of the hail that fell in town measured almost 3 inches in diameter.

Blackwell, Okla.—The tornado struck Blackwell, Okla., about 2127 CST. It traveled from south to north with almost complete destruction over a path about two blocks wide, and considerable destruction extended 3 or 4 blocks farther on either side. Mr. Nave, who lives just south of the south city limits of Blackwell, reported a short period of wind and hail (about 2 inches in diameter). Then followed a quiet during which he went outside. Instead of the air being cool following the squall, it was "hot." Then the tornado funnel was sighted approaching from the south. It came with "the roar of forty freight trains." There was lightning all around but not in the immediate vicinity of the funnel.

Mr. B. H. Jones living on the north side of Blackwell, about 4 blocks from the damaged area, reported squally weather with wind, rain, and hail followed by a short period of quiet. He went outside, heard the "roar," and immediately sought shelter. Upon emerging, he saw the tornado funnel leaving town in a north-northeasterly direction, still in contact with the ground.

The pattern of debris at Blackwell gave the appearance of more inflow than actual rotation in the sense that trees to the west of the center of the path had been blown eastward, and those to the east had been blown westward. Debris from the buildings yielded little information because of the difficulty in being able to determine from whence it came.

Eight Miles West of Arkansas City, Kans.—Following are two eyewitness accounts from an area about 23 miles north-northeast of Blackwell close to U. S. Highway 166, about 8 miles west of Arkansas City, Kans., Mr. and Mrs. Post, who live at a farm just south of the highway, report that their power failed at 9:58 p. m. (time ascertained from a stopped electric clock) followed in about 5 minutes by hail and shortly thereafter by a terrible roar. This was followedby a quiet lull which lasted probably less than a minute. The storm struck again, blowing down several large trees. These trees lying down toward the east must have been felled by a west wind. The couple was in the house the entire time, but looked out the windows during the course of the storm. When the initial roar was heard only blackness was visible to the south. After the tornado had passed over, it was clearly visible to the north against the background of almost constant lightning farther to the north. Neither Mr. nor Mrs. Post experienced any sensation of change of pressure during the course of the storm.

(*Continued on p. 238*)

HAS THE AMOUNT OF CARBON DIOXIDE IN THE ATMOSPHERE CHANGED SIGNIFICANTLY SINCE THE BEGINNING OF THE TWENTIETH CENTURY?

GILES SLOCUM

U. S. Weather Bureau, Washington, D. C.

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ABSTRACT

The search for causes of the rising temperatures in some geographic areas during the twentieth century has directed interest toward the amount of atmospheric carbon dioxide (CO_2). If the carbon dioxide added by the combustion of fossil fuels remains as a net increase, any temperature-changing effects of its presence as a minor constituent of the atmosphere should be cumulatively operative as the amount increases.

In this paper, the physical knowledge of atmospheric CO_2 is examined and the available nineteenth and twentieth century observations of the atmospheric CO_2 concentration are summarized to ascertain the extent to which they corroborate claims that the amount of atmospheric CO_2 has increased since the nineteenth century. In the light of the uncertainty of both physical knowledge and of statistical analysis, it is concluded that the question of a trend in atmospheric CO_2 concentration remains an open subject.

1. INTRODUCTION

This report examines the physical knowledge of atmospheric CO_2 and summarizes the available nineteenth and twentieth century observations of the atmospheric content of CO_2, to ascertain how far they corroborate claims that the amount of carbon dioxide in the atmosphere has increased since the nineteenth century. Charts and tables are included, showing the locations, periods of record, numbers of measurements, and the ranges of values of the observed CO_2 concentration.

The amount of carbon dioxide in the atmosphere is actually little more than a trace [18, 23]. That dissolved in the waters, or combined as carbonates, etc., in the crust of the earth, is much greater. Goldschmidt [15] presents a table, showing the location of the earth's CO_2 and potential CO_2. It is the source for table 1. From this table, it appears that about 0.005 percent of the earth's crustal carbon is in the atmosphere as CO_2.

Important climatic effects are attributed to this small percentage of carbon dioxide in the air, and, according to Callendar [6, 7, 9] and Plass [24], a significant increase in the concentration of CO_2 would noticeably raise the surface temperature of the earth because of the "greenhouse effect."

TABLE 1.—*Kilograms of CO_2 and potential CO_2 per square centimeter of the earth's surface (After Goldschmidt [15])*

A. In the carbonates in sedimentary rocks	6.56.
B. In coal, bitumen, humus, and the biosphere	0.67 to 3.1.
C. In sea water	0.020.
D. In the atmosphere, mainly CO_2	0.0004.
Total	7.3 to 9.7.

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In 1938, Callendar [6] suggested that the combustion of the fossil fuels, such as coal, lignite, petroleum, etc. may be causing such an increase. At that time, according to his estimate, 4.3 x 10^9 tons of CO_2 per annum were being added to the atmosphere in this way. He gave the total added between 1887 and 1937, after allowing for an accelerated rate of burning as time went on, as about 1.5 x 10^{11} tons. So large an amount added so quickly would, he suggested, be absorbed into the earth's waters at a much slower rate. Assuming that other natural processes, such as the biological exchange, be in balance, the result would be an increase of atmospheric CO_2 with time. He estimates that 2000 to 5000 years will be required before we may expect the atmospheric content to reach equilibrium with the rate of oceanic absorption.[1] Since the acceleration in the rate of industrial combustion may not cease for some time [17], the consequently increasing CO_2 in the atmosphere would increase the absorption of outgoing radiation, and the surface layer of the atmosphere would become warmer.

In support of this view, Callendar [7] selected from the published records of determinations of CO_2, made between 1867 and 1935, those which he considered the most accurate. On the evidence of these records, he found that the CO_2 had apparently increased since 1900 by about 6 percent.

Figure 1, after Glueckauf [14], shows the increase in content, according to Callendar's selected data. To Glueckauf's plotted points have been added more recent data, including Callendar's 1949 computed value [9], and other

[1] Suess [26], however, estimates that the "average lifetime of a CO_2 molecule in the atmosphere before it is dissolved in the sea will lie between 20 and 50 years."

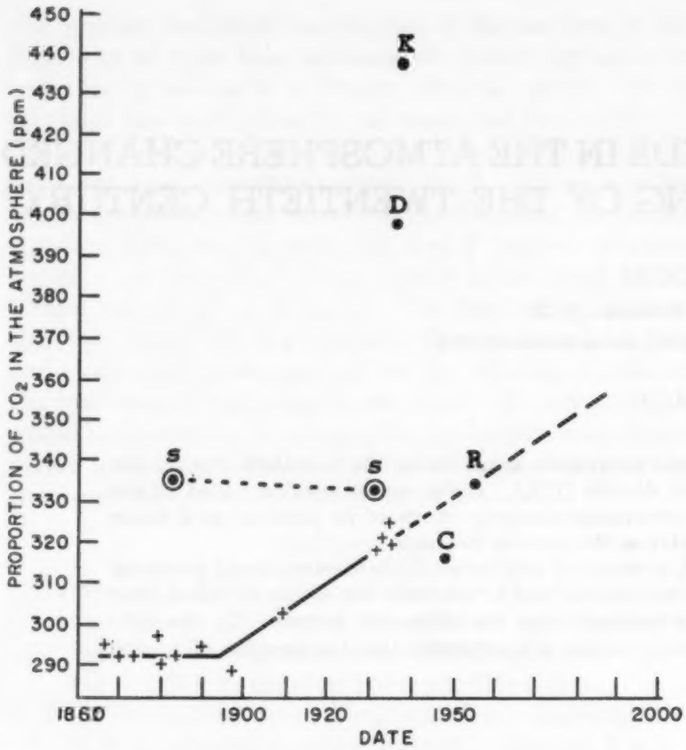


FIGURE 1.—Trend in CO_2 content of the earth's atmosphere (selected data). Adapted from Glueckauf [15]. To Glueckauf's values (+) have been added those of Duerst (D), 500 observations [13]; Kreutz (K) 25,000 observations [21]; Callendar's latest estimate, 1949 (C) [9]; and the means derived in the present paper (S).

recent estimates mentioned at various points in the present paper.

Buch [5], used his own observations (1932–1935) taken in scattered high latitudes in the North Atlantic ocean and its estuaries, as representative of the concentration of atmospheric carbon dioxide at that time, and the same sources as those selected by Callendar to represent the content in the late nineteenth and early twentieth centuries. Then, comparing these latter data with his own newly observed values, he came to substantially the same conclusion as did Callendar.

Recently there have been independent studies which are at least consistent with Callendar's. Among these recent studies may be mentioned those of Brown [3], who, in 1952, determined the C^{12}/C^{13} ratio in tree ring samples. He found evidence that this ratio is, on the average, greater in the younger samples than in the older. This indicates, he suggests, that "carbon dioxide in the air has been diluted in recent years by carbon dioxide from industrial sources," and [4] that the total "Carbon dioxide content of the atmosphere may be increasing, or at least may not be in equilibrium with the oceans." Dingle [11], by physical reasoning, arrives at the conclusion that the CO_2 content of the atmosphere at present exceeds 0.03 percent, which is in excess of the proportion Callendar estimates for the nineteenth century.

Hutchinson [19] has stated that, "There can be little doubt that during the first half of the twentieth century the mean CO_2 content of the air in north temperate latitudes has increased." Callendar has thus had a number of supporters in whole or in part.

Independent opinion has not, however, been unanimous in support. At the time Callendar delivered his 1938 paper [6], Mr. J. H. Coste suggested that the accepted CO_2 content had at the turn of the century been considered to be about 0.04 percent, and not the 0.029 percent indicated by the measurements Callendar cited. Mr. Coste then asked, since the value, 0.04 percent, is a higher percentage than the average value of about 0.032 percent Callendar found for the 1937 CO_2 content, can we be sure that there has been any net increase at all in the percentage of CO_2 in the atmosphere?

2. PHYSICAL EVIDENCE

There are processes which may deplete the increased concentration of CO_2 produced by combustion, and others which may be more important than combustion of fossil fuel in increasing the concentration, at least temporarily. Callendar does not consider them relatively important, but it seems logically tenable to suppose that a relatively slight increase in the rate of biologic absorption of CO_2 might nearly, or even more than, compensate for any increase in its evolution from other sources, such as industrial combustion.

Moreover, Hutchinson [19] suggests that with the expansion of industry through the past century, agriculture also expanded, and that there is a far greater opportunity for loss of respiratory CO_2 from soil in arable land than in forest land. He therefore doubts the validity of Callendar's explanation of the source of an increase in the amount of CO_2.

Dingle [11], in discussing Callendar's findings, points out the complexities of determining the amount of CO_2 in the world's atmosphere as a whole. Measurements at one or a few localities over a limited period of time are inadequate, since the concentration of carbon dioxide varies in air masses of differing trajectories. He suggests that increases in the concentration of observed CO_2 might be due to changes in the general atmospheric circulation rather than necessarily mainly due to a worldwide increase in CO_2 concentration. He holds this to be a more attractive physical hypothesis to explain any increase in the observed CO_2 value than is Callendar's thesis that the higher temperatures are due to an increasing concentration in the atmosphere as a whole.

Since this paper was initially prepared for publication, two studies by Suess [25, 26] have become available. He cites the fact that fossil carbon does not contain appreciable C^{14}, and presents evidence that the proportion of C^{14} contained in tree rings has decreased slightly since the nineteenth century. In its place is a greater proportion of C^{12}. The decrease in the ratio is, however, greatest

TABLE 2.—*Physical and chemical processes adding or extracting massive quantities of CO_2 to or from the atmosphere (after Hutchinson [19])*

Process or category	Gross emission ($\times 10^{12}$ grams/year)		Gross absorption ($\times 10^{12}$ grams/year)	
	At least	But not more than	At least	But not more than
Volcanic output of CO_2 [19]	30	70		
Oceanic sedimentation of Carbonate [19]			30	70
Oceanic Emission [19]	700	2,500		
Oceanic Absorption [19]			700	2,500
Continental Photosynthesis [2]	87,500	88,500		
Continental Respiration [2]			87,500	*92,000
Consumption of fuels	4,000 [16]	6,100 [20]		
Grass and forest fires [19]	5,750			
Total Atmospheric Carbon Dioxide is probably between 2,250,000 and 2,750,000 $\times 10^{12}$ grams				

*Adding to the maximum photosynthesis estimate, a half of the highest estimate of production by industrial consumption of fuels.

near concentrations of industry, and is much less in the case of a tree which grew in Alaska than in the cases of trees near dense population centers. Suess concludes that ". . . the world-wide contamination of the earth's atmosphere with artificial CO_2 probably amounts to less than one percent."

Brown's [3, 4] evidence from tree rings of the dilution of CO_2 has been suggested as showing that there has been an increase in the amount of CO_2. This does not necessarily follow. It can be shown that dilution would be the expected result of any large replacement of natural by fossil carbon dioxide. Such dilution would occur whether the total amount in the atmosphere be gradually increasing, remaining approximately stationary, or decreasing. Indeed, the replacement would be most pronounced, and, therefore, most detectable in an atmosphere with decreasing CO_2 concentration. Thus far only Brown's abstracts are available. In them, he states his conclusions in strictly qualitative terms. Demonstration that the trend is either up or down awaits a quantitative discussion of his findings and of whatever compensating forces in either direction enter as complications. What Brown seems to have confirmed thus far is the already established fact that great quantities of fossil carbon have been turned into atmospheric CO_2.

Thus, students of the subject differ. That is, physical reasoning has not as yet shown that CO_2 is necessarily increasing as a result of the addition of combustion gases. There remains the statistical approach, that used by Callendar. The current knowledge from a quantitative standpoint is summarized in table 2.

3. STATISTICAL EVIDENCE

With a dependence on statistical evidence, the mathematically established statistical criteria for significance of results must rule the degree of confidence with which conclusions may be drawn from the original data. Callendar's and Buch's averages appear, as presented in figure 1, to show an increase in CO_2 from the late nineteenth century to the beginning of the middle third of the twentieth. Their comparisons are, however, based on a narrow selection of values from a much larger body of data, scattered through the scientific literature of the past century. It may be granted that the data they used are probably quite accurate averages for the time, place, meteorological conditions, etc., of observation. The question remains, however, are all the measurements which they did not use, inaccurate?

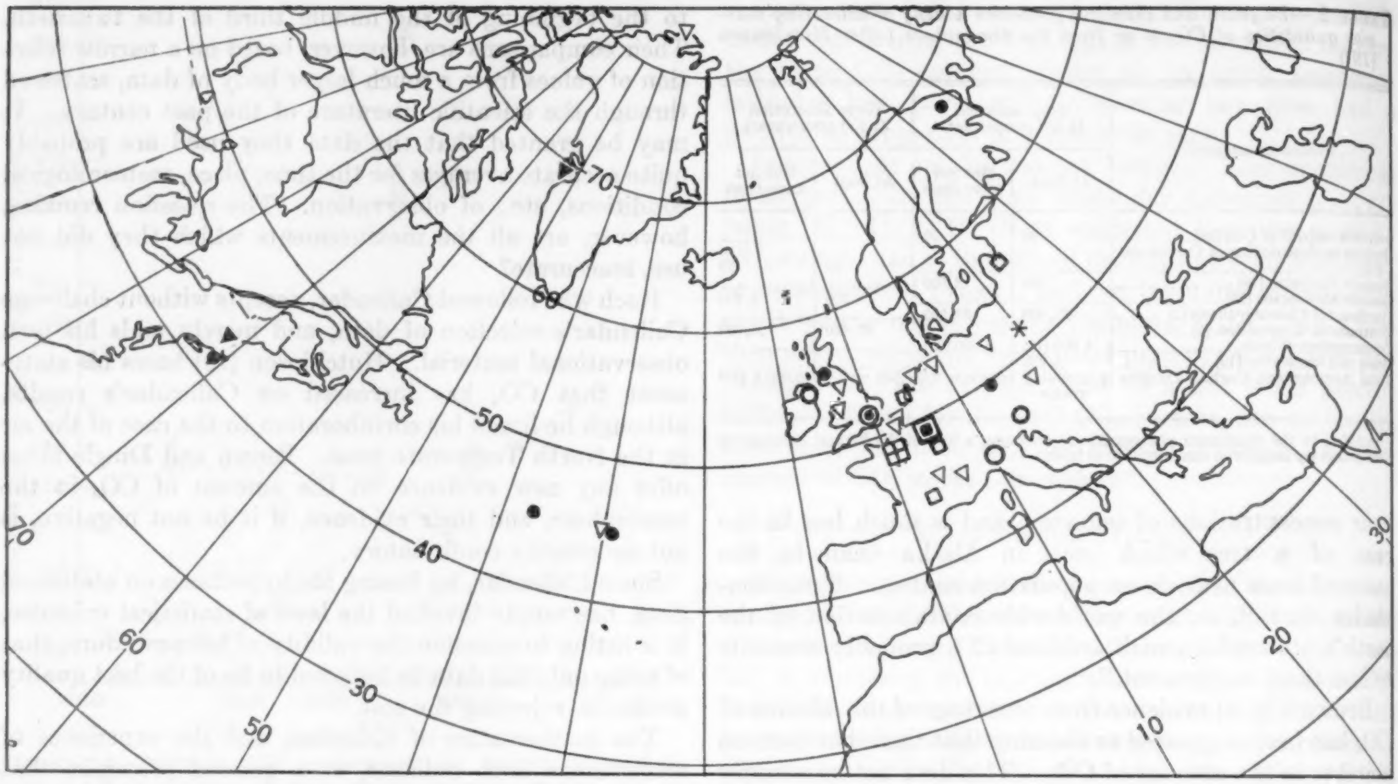
Buch who followed Callendar, accepts without challenge Callendar's selection of data, and merely adds his own observational material. Hutchinson [19] bases his statement that CO_2 has increased on Callendar's results, although he limits his corroboration to the case of the air in the North Temperate zone. Brown and Dingle alone offer any new evidence on the amount of CO_2 in the atmosphere, and their evidence, if it be not negative, is not necessarily confirmatory.

Since Callendar, by basing his hypotheses on statistical data, has tacitly invoked the laws of statistical evidence, it is fitting to examine the validity of his procedure, that of using only the data he believed to be of the best quality available, rejecting the rest.

The mathematics of statistics, and the experience of statisticians both indicate, as a general principle, that arbitrary rejection of data, without specific knowledge of their unreliability or unapplicability, is questionable. Although the purpose of such a procedure may be to remove an observational or sampling bias that is known to be present, selection of the data to be used will often introduce a greater source of error than that which it was intended to remove.

At best, the omission of part of the data is not as necessary or as helpful as might appear at first thought, since it can be shown that when the means of two sets of data are compared, the presence of a given average bias in each set will not affect the difference nor the standard error of this difference, except as an added contribution to the variance of the sample. If, however, some of the data be selected to the exclusion of the rest, for the purpose, perhaps, of reducing the magnitude of the residual variance, due to crudity in some of the measurements, then, in addition to any unintentional bias that might be introduced in the comparison of the means, there might also result an underestimate of the standard error of the difference, due to the mistaken rejection of those of the extreme values which actually belong to the distribution. The result may be an entirely spurious accuracy in the means, which leads to unjustified conclusions.

In the light of these considerations, a reexamination of the entire body of available measurements of the relative proportion of CO_2 in the atmosphere may have some value. Fortunately, Effenberger [13] has compiled what seems to be a fairly complete list of the published observations up to 1940. He has indicated the sets of determinations used by Callendar [8]. More recently, the American Meteoro-



Symbol	Period of Observations	Location	No. of Obs.	CO_2 content of atmosphere (parts per million) Min.	Mean	Max.
⊞	1816-1827	France	- -	370	410	620
*	1844	Prussia	- -	210	400	420
▽	1866-1879	45°N, 30°W	4	- -	270	- -
▽	1866-1879	Greenland	3	480	550	640
▽	1866-1879	England	26	- -	310	- -
▽	1866-1879	England	53	210	296	410
▽	1866-1879	France	80	270	292	350
▽	1866-1879	France	89	- -	291	- -
▽	1866-1879	Germany	1,034	270	292	350
▽	1866-1879	Germany	347	210	330	420
▽	1866-1879	Austria	295	300	340	410
▽	1866-1879	Switzerland	- -	210	330	420
▽	1866-1879	France	- -	- -	410	- -
▽	1866-1879	France	- -	- -	300	- -
□	1880-1889	Belgium	525	260	294	350
□	1880-1889	E. Baltic	266	- -	300	350
□	1880-1889	France	1,000	240	292	360
□	1880-1889	France	64	- -	287	- -
□	1880-1889	France	- -	- -	290	- -
○	1890-1898	Ireland	64	- -	289	- -
○	1890-1898	England	92	- -	294	- -
○	1890-1898	Austria	- -	200	380	550
▼	1904-1919	U.S.	645	- -	303	- -
▼	1904-1919	Greenland	59	- -	480	700
■	1920-1929	France	17 137	180	290 310	590
●	1930-1939	U.S.	- -	- -	329	- -
●	1930-1939	45°N, 37°W	28	152	318	368
●	1930-1939	45°N, 29°W	53	- -	320	- -
●	1930-1939	Scotland	152	- -	324	- -
●	1930-1939	England	- -	- -	310	350
●	1930-1939	Finland	95	- -	321	- -
●	1930-1939	Germany	25,000	- -	438.5	- -
●	1930-1939	Italy	500	240	400	790

Figure 2.—Geographic distribution of selected CO_2 content measurements that have been made in the Northern Hemisphere and the data available for each location.

logical Society [1] has published a "Bibliography on Carbon Dioxide in the Atmosphere." From this source and elsewhere, references have been found and some additional, more recent, data have been compiled. The geographic distribution of these observations of CO_2 atmospheric content and other data listed by Effenberger and the other sources used in these summary tables, are shown in figure 2. This figure shows the means and the highest and the lowest values of the atmospheric concentration found during each of the observational programs represented. Where available, the numbers of observations, on which the means were based, are given.

The asterisk and boxed plus sign in figure 2 show the data for the observations which were made earlier than the first of those selected by Callendar. One set of observations was made in 1816, the other in 1844. The observations shown by open symbols represent the period 1866–1901 from which Callendar selected his values for the latter part of the nineteenth century. During this period, the consumption of fossil fuel had not become as great as it was between 1901 and 1930, a period represented roughly by the bulk of the data charted as solid symbols. Where a closed symbol appears inside an open symbol, observations were made during both of the latter periods.

In table 3, the mean values shown in figure 2 are reclassified to show the values used by Callendar for the

Table 3.—*Mean CO_2 values, in parts per million. Determined by observation in the period 1816 to 1940. Compares CO_2 content for observations used by Callendar with that for observations not used by him. [Arrangement is in order of magnitude.] (after Effenberger [13] except as noted)*

Nineteenth Century (1816 to 1901)			Twentieth Century (1904 to 1935) (1936 to 1940) 1904			
				Means not used by Callendar		
Means used by Callendar	Means not used by Callendar	Documented as anomalous data	Means used by Callendar	Rejected as inaccurate etc.	Published too late to be available	Documented anomalous data [22]
287	270	[a] 460	303	290	400	[c] 480
289	290	[b] 560	318	310	438.5	
291	300		320	[d] 310		
292	300		321			
292	320		324			
292	330					
294	330					
294	340					
295	350					
296	380					
	400					
	410					
	410					
	470					
	550					
Means 292	363		317	303	419	
Combined means 335				334		

[a] Observed on rainy days
[b] Observed on days with snow
[c] Krogh's [22] data
[d] Not listed by Effenberger. Cited by Callendar, but not included in his means

nineteenth and for the twentieth centuries, and three categories of observations not used by him. Each value, as in figures 1 and 2, is a mean of a group of observations, varying from 3 to about 25,000.

Figure 3 shows the majority of these determinations grouped in another way. Here, the means of the sets of observations, for each of the principal regions where measurements were made, are shown for: British Isles (fig. 3A); France and Switzerland (fig. 3B); Central Europe, including Germany, Austria-Hungary, the eastern Baltic States, and Denmark (fig. 3C). The length of line, representing each mean, shows the length of time the observational program continued. It can be seen from this figure that the majority of programs were of short duration, and from the table accompanying figure 2 that in some cases only a few observations were made.

Reference to the three charts in figure 3 does not reveal any significant trend in CO_2 content, such as is so clearly shown in figure 1. Indeed, after excluding values which the observers themselves have designated as non-representative, but not any of the others, then the mean value for the nineteenth century is 335, and for the first third of the twentieth century 334 parts per million. Such a close approach to identity of values for the two periods is, of course, an accident. Referring to the texts of the papers from which Effenberger made his tabulations, it appears that there has been wide variability in the means found for differing geographical regions, on land and on sea, and from one synoptic weather condition to another. The data-gathering programs were conducted by mutually independent observers, using differing techniques. There

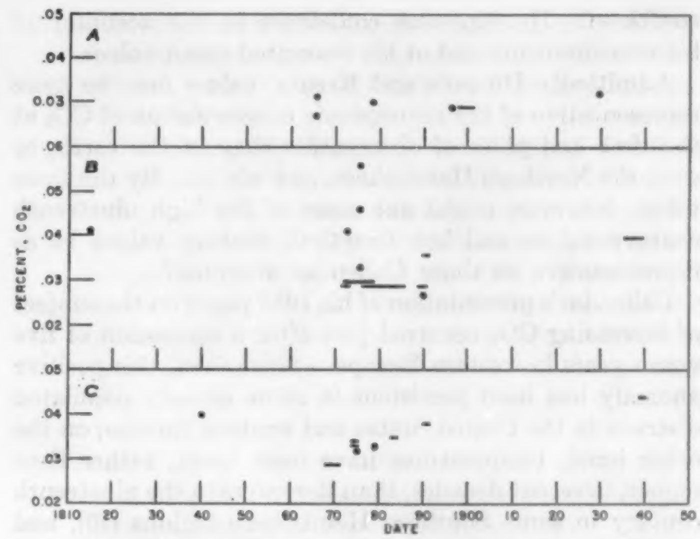


Figure 3.—Proportional amounts of atmospheric CO_2, in parts per million, measured in (A) the British Isles, (B) France and Switzerland, and (C) Germany, Denmark, East Baltic States, and Austria-Hungary. Length of line denotes length of time observational program continued. Dots are used for periods less than one year. The line segment in (C), at 1939–40 and showing 438.5 ppm, is based on more observations than all other points and line segments on all three charts combined.

are so many possible sources of variability, that there is no basis for any claim, based on these data, that the CO_2 content of the atmosphere has remained anywhere near constant. Similarly, there is inadequate basis for a claim that Glueckauf's trend line approximates the recent trend of the actual carbon dioxide content of the earth as a whole.

The means that Callendar rejected from the nineteenth century records are, in the main, indicative of higher values than those he accepted. He points out that the accuracy of observations improved as time went on, and that early techniques tended to give too high values. Statistically speaking, the data in table 3 could well be drawn from a population having these properties.

The three values for the twentieth century, however, which Callendar rejected average lower than those he accepted. This does not demonstrate that his choice was bad, but the fact that he considers so many nineteenth century values to be overestimates and two twentieth century values to be underestimates raises a question about his method of selection.

Since techniques have been improving, the latest observations should be the most accurate. Duerst [12] and Kreutz [21] found values of 400 and 438.5 parts per million, respectively, from observations made in 1936 and 1939. Duerst bases his mean on 500 observations, a reasonably large number, if his techniques are correct. Kreutz made about 25,000 observations. This is more than were made in all other herein listed observing programs

combined. He expresses confidence in the accuracy of his measurements and of his computed mean values.

Admittedly Duerst's and Kreutz' values may be more representative of the atmospheric concentration of CO_2 at the time and place of observation than of the earth, or even the Northern Hemisphere, as a whole. By the same token, however, might not some of the high nineteenth century values and low twentieth century values be as representative as those Callendar accepted?

Callendar's presentation of his 1938 paper on the subject of increasing CO_2 occurred just after a succession of five warm years in western Europe. Since then, this positive anomaly has been persistent in some densely populated districts in the United States and western Europe; on the other hand, temperatures have been lower, rather than higher, in recent decades, than they were in the nineteenth century in some Southern Hemisphere regions [10], and elsewhere. Can we be entirely sure that the earth as a whole has warmed up enough to require an increase in CO_2 in the air to explain it?

At any rate, it is apparent that, if we use the statistical approach, different degrees of selectivity in determining which data to include are productive of differing final results.

4. CONCLUSIONS

Is the CO_2 increasing? Much seems to depend on the objectivity of Callendar's decisions as to which data to keep.

In the light of the uncertainty of both physical knowledge and of statistical analysis in determining whether the relative proportion of carbon dioxide in the air is increasing significantly, remaining almost constant, or even decreasing slightly, the final word cannot as yet be considered to have been said. Instead, the subject remains open, either until another chemist critically evaluates the accuracy of the existing data, or else until more and better-organized data are available.

All this does not refute Callendar's thesis. The available data merely fail to confirm it. The positive evidence that the CO_2 has increased is inconclusive, but seems strong enough to reward further study, and the time seems ripe for new research.

It may be hoped that the collection of standardized measurements of CO_2 can be made a part of the 1957–58 International Geophysical Year program. Once a dependable set of observational data has been assembled, the evidence of the old observations can perhaps be reevaluated. If such new reevaluation proves impracticable, even then a reliable set of new worldwide observations can serve as a basis for comparison in future years.

In summary, the data, at present available, are inadequate as they now stand to prove or disprove a statistically significant trend in CO_2 concentration in the atmosphere. If and when an upward trend has been demonstrated, and its cause ascertained, it will then be valid to base physical explanations of atmospheric events on the assumption that CO_2 is increasing. Meanwhile, Callendar's interesting extrapolations (through the 22d century) of the effects of burning up of the world's fuel, stimulate the interest of the speculatively minded.

ACKNOWLEDGMENTS

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THE WEATHER AND CIRCULATION OF OCTOBER 1955[1]

A Month with a Double Index Cycle

CARLOS R. DUNN

Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

1. GENERAL CIRCULATION

The general circulation during October 1955 was characterized by four record-breaking index oscillations. During this period the 5-day mean zonal index, which expresses the strength of the average zonal westerlies between 35° and 55° N. in the Western Hemisphere, underwent two cycles, each with a period of approximately two weeks, as shown in figure 1. Inspection of the entire file (1941 to date) of index graphs revealed that the large amplitude and short period of this month's index fluctuations were unique. A similar change took place in October 1946, but then only one cycle occurred with a maximum variation of 5.2 m. p. s. This October's index, which was initially near normal, was subjected to weekly changes of as large as 6 to 7 m. p. s. There were periods of both high and low index as the circulation fluctuated back and forth between fast zonal and strong meridional flow.

At the beginning of October temperate-zone westerlies were fast at all longitudes. The first diminution occurred in the Atlantic and then, over a period of weeks, migrated upstream to affect the Pacific during the final week of October. This westward movement was irregular and it often appeared that a rather well matched "tug-of-war" existed between the initially fast westerlies in the Pacific and the blocking phenomenon in the Atlantic. Ultimately the low index regime dominated the circulation and set the stage for below normal westerlies during the entire month of November. Associated with these index changes were very different short-period mean circulation patterns which warrant some discussion.

700-mb. 5-day mean charts, figure 2, were selected to correspond with the maxima and minima of the index cycles, which were one week apart, and to illustrate the changes and extremes in the circulation that occurred during this month. The mean flow for October 8–12 (fig. 2A) was essentially one of high index over the entire Northern Hemisphere. In the Western Hemisphere the index of 13.1 m.p.s. was the highest 5-day mean value of the month. Downstream from the confluent pattern in the western Pacific the westerlies were concentrated into a very narrow jet stream. The waves were long and of small amplitude. The closed anticyclone in the Davis Strait, which originated early in the month, is particularly noteworthy because of its persistent nature and because of its future effects on the circulation and weather.

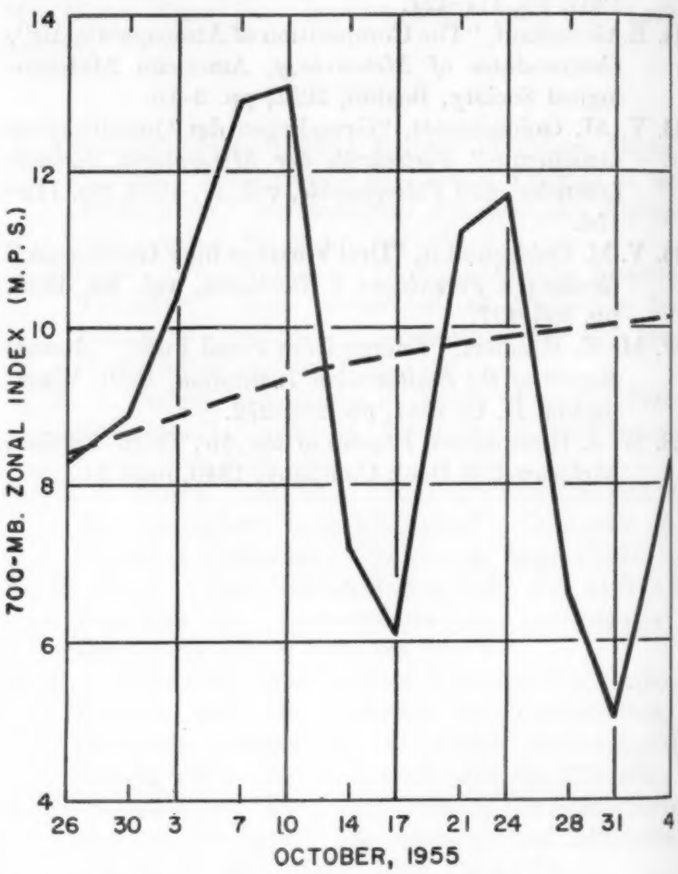

FIGURE 1.—Time variation of temperate-latitude zonal index (average strength of zonal westerlies in meters per second between 35° N. and 55° N.) at 700 mb. over the Northern Hemisphere from 0° westward to 180° longitude. Solid line connects 5-day mean zonal index values (plotted at middle of 5-day periods) for October. Dashed line shows variation of normal zonal index values. Note the unprecedented double index cycle.

One week later, October 15–19 (fig. 2B) at the minor index minimum (6.1 m. p. s.), a rapid, intense breakdown and amplification of the circulation occurred. Some decrease in wind speed was apparent in the Pacific, but the largest changes were downstream in the United States and Atlantic. The intensifying anticyclone in the Greenland region was accompanied by southward displacement

[1] See charts I–XV following p. 247 for analyzed climatological data for the month.

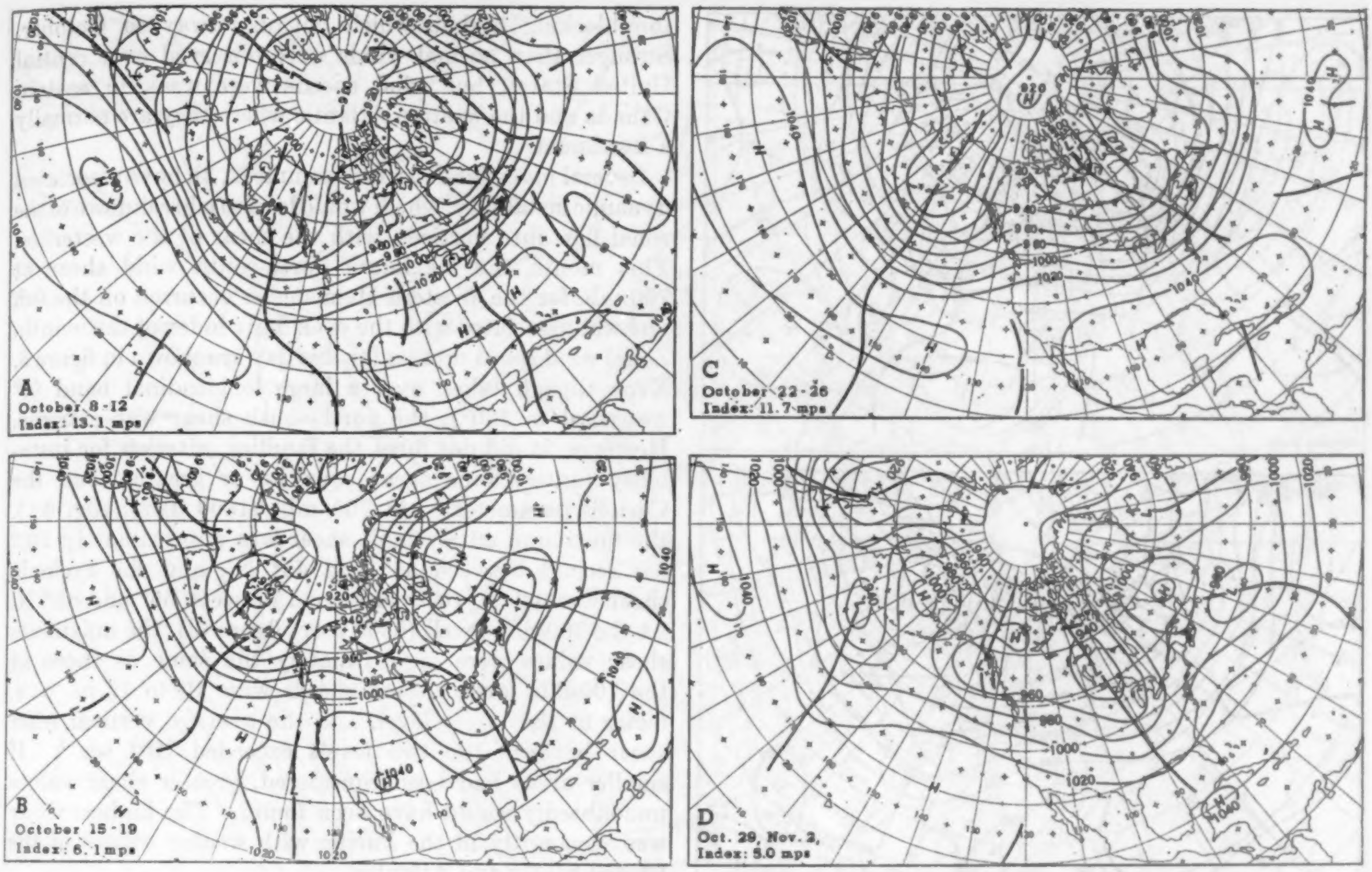

FIGURE 2.—Five-day mean contours at 700 mb. (in tens of feet) for four periods one week apart which correspond to the maxima and minima of the double index cycle (fig. 1). Intense, weekly oscillations were characteristic of October 1955.

of vigorous cyclonic conditions into Europe and eastern North America. Associated with this Atlantic blocking pattern was the short wave length which resulted from the addition of a new major trough in the Atlantic. The waves were generally stationary or retrogressive.

The zonal westerlies (index of 11.7 m. p. s.) again dominated during the period October 22–26 (fig. 2C) and the description of the earliest mean chart (fig. 2A) generally applies except that the jet stream was less concentrated. In the Atlantic and eastern North America the vortical pattern of the previous week was replaced by the eastward march of the strong westerlies, but weak blocking was still discernible. 700-mb. mean heights ranged up to 360 feet above normal in the Davis Strait and down to 230 feet below normal just east of Labrador. There was a decrease in wave number as the Atlantic trough filled. General progression of the troughs prevailed.

The minimum low index (5.0 m. p. s.) regime of the month was October 29–November 2, (fig. 2D). There was a major breakdown of the zonal flow into numerous vortices and truncated troughs. This time, in contrast to two weeks prior, the westerlies decreased farther upstream in the Pacific, where a strong blocking High now appeared in the Bering Sea.

It now has been emphasized that two basic regimes existed in October. If the monthly mean circulation is divided into two 15-day means, the predominating regimes of the semi-months are brought into focus. The first half, October 1–15 (fig. 3A) represented mostly the high index regime (11.0 m. p. s.), especially in the Pacific where a stronger than normal westerly flow was observed east of the confluence zone along the Asiatic coast. The positive 700-mb. height anomaly in the Pacific was firmly established in August [1] and has been a long-period cornerstone of the general circulation. In eastern North America mean heights were above normal, with the maximum anomaly in the Davis Strait. Anticyclonic flow existed along the eastern seaboard.

During the latter half month, October 16–30 (fig. 3B) the low index (average 8.6 m. p. s.), blocking regime predominated. The general circulation responded in typical fashion to the persistent positive anomaly in the Greenland area as major 700-mb. height falls occurred to the south over the eastern United States, Labrador, and European areas. The unusual cyclonic conditions over Europe and the strong, northerly anomalous flow produced some abnormally early freezing weather.

Even though large fluctuations occurred during the

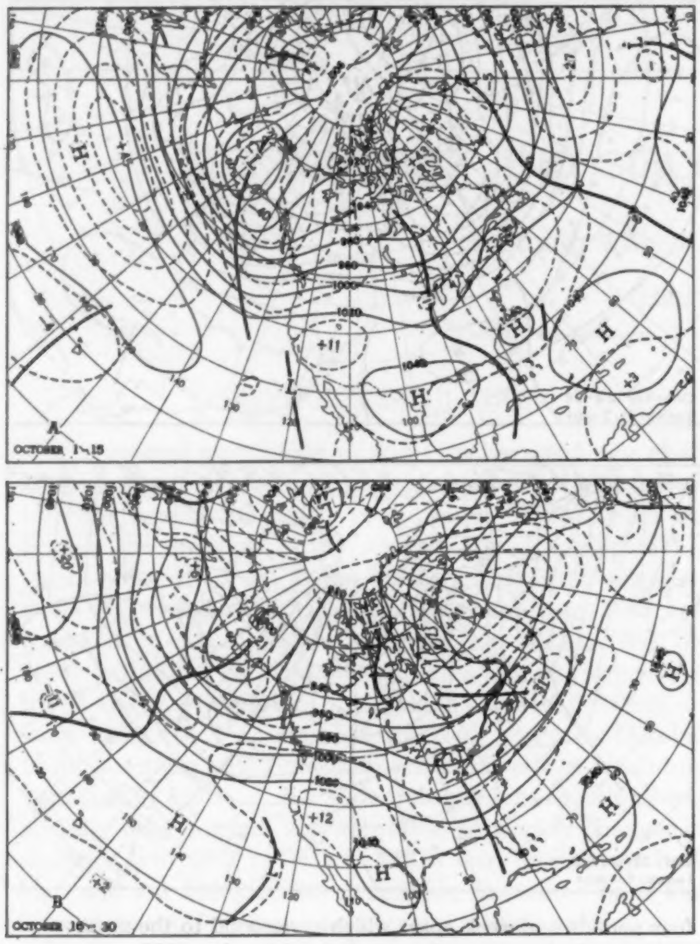

FIGURE 3.—Fifteen-day mean contours and height departures from normal at 700 mb. (both in tens of feet) for periods (A) October 1–15, 1955 and (B) October 16–30, 1955. Heights continued above normal in western United States and Greenland region but fell away in eastern United States. High index dominated first half-month, low index the latter half.

month there were also persistent features which were outstanding in the monthly mean 700-mb. height (fig. 4). Above normal heights in the Pacific at middle latitudes, coupled with subnormal values over eastern Siberia and Alaska, resulted in a high index circulation in the Pacific. This contrasted with the blocking regime in the Atlantic sector, where heights averaged above normal from the Greenland area to southern New England and below normal over the central Atlantic and the eastern United States.

The spatial distribution of the 700-mb. monthly mean wind speed and anomaly (fig. 5) shows that the fastest winds, greater than 20 m. p. s., were in the central Pacific, while a somewhat weaker and more diffuse flow existed over the United States and the Atlantic. A northward displacement from normal of the Pacific wind maximum produced zonal bands of above and below normal winds. In the United States a greater than normal southward displacement of the westerlies, which had been abnormally far north throughout the summer [1], was representative of the blocking regime which got underway in October. Stronger than normal winds were observed over central United States, but wind speeds were weak in eastern Canada and the western Atlantic where they are normally a maximum.

Several investigations, for example [2, 3], have associated dynamic instability, which would lead to a breakdown of the zonal flow into vortices, with the shear of the westerlies. This month the maximum north-south wind shear at 700 mb. for the Western Hemisphere occurred on the 9th and was associated with the peak daily index of the month. Zonal wind speed profiles for this day are shown in figure 6. Even though taken over a large longitudinal band (0° westward to 180°), the north-south shear was extreme. However, it did not meet the familiar criterion for instability (anticyclonic shear equal to or greater than the Coriolis parameter). At 700 mb. (1500 GMT), (fig. 6A), the maximum anticyclonic shear was approximately 10^{-5} per second between 35° and 45° N., and the cyclonic shear was 0.2×10^{-4} per second between 55° and 65° N. At the 200-mb. level, (0300 GMT) figure 6B, the maximum shear values were approximately the same as those at the 700-mb. level. Wind speeds were 10 to 12 m. p. s. faster at the upper level, and the average vertical wind shear between the two levels exceeded 10^{-3} sec^{-1}. If smaller areas had been considered, greater shear values undoubtedly would have been found. The highest shear was apparently in the Pacific with weaker values in the United States and Atlantic.

2. WEATHER AND CIRCULATION IN THE UNITED STATES

In the United States the circulation pattern became progressively more anticyclonic in the West and cyclonic in the East from September [4] through October. In some areas there was even a change from September to October in the sign of the relative vorticity at the 700-mb. level and the pressure departure from normal at sea level (Chart XI, inset). Therefore the departure of monthly average temperature from normal (Chart I-B), showed little month-to-month persistence except for two small areas: (1) a warm region spreading south-southwestward from Wyoming, and (2) a region of subnormal temperatures in the far Northwest, where small areas have experienced cooler than normal weather for nine consecutive months.

It is interesting that, in spite of the existence of two regimes in October, the monthly mean flow (fig. 4) generally determined the weather over the United States. After the first week, which was warm in the Southeast, there was little variation in the country's temperature, and each weekly anomaly resembled the monthly mean. However, New England experienced some extremely variable weather. For example, Boston, Mass., reported a record-breaking maximum temperature of 82° F. on the 11th, but frost on the 23d.

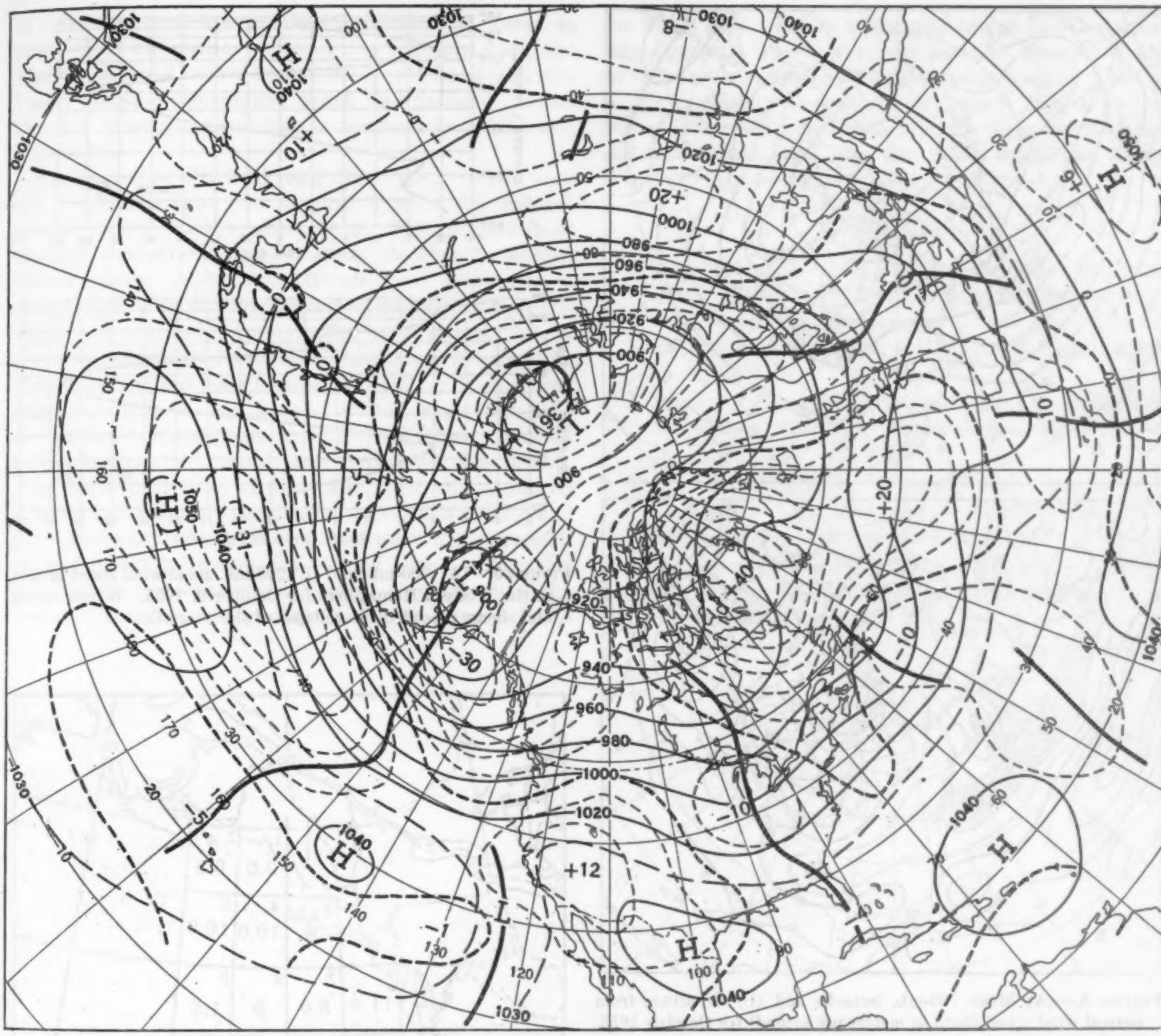

FIGURE 4.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for October 1955. Persistent above normal heights in the mid-Pacific and Davis Strait were prominent features of the general circulation. Anticyclonic and cyclonic conditions prevailed in western and eastern United States respectively.

Throughout most of the western mountains, where the circulation was anticyclonic and 700-mb. height departures were positive, temperatures averaged above normal. The maximum anomaly (+6° F.) was observed in Montana where the foehn effect was most pronounced. The observed temperatures of 92° F. on the 10th at Glasgow, 82.5° F. on the 18th at Billings, and 76.6° F. on the 25th at Helena were new highs for that late in the fall. Few polar anticyclones formed in the Canadian source region, where mean sea level pressure anomalies were negative (Chart XI, inset), and Canadian polar outbreaks were scarce and weak (Chart IX). This absence of polar air masses contributed to above normal temperatures in the northern tier of States east of the Continental Divide. On the other hand, there were frequent intrusions of polar Pacific air into southeastern States, where Pacific air was cool enough to produce subnormal temperatures, especially under the existing cyclonic flow. Augusta, Ga., where the maximum negative anomaly was observed, equalled its minimum temperature record of 38° F. on the 20th.

Little rainfall (Charts II and III) was observed in most parts of the Southwest and Great Plains, where the 700-mb. mean flow was anticyclonic. Southern California

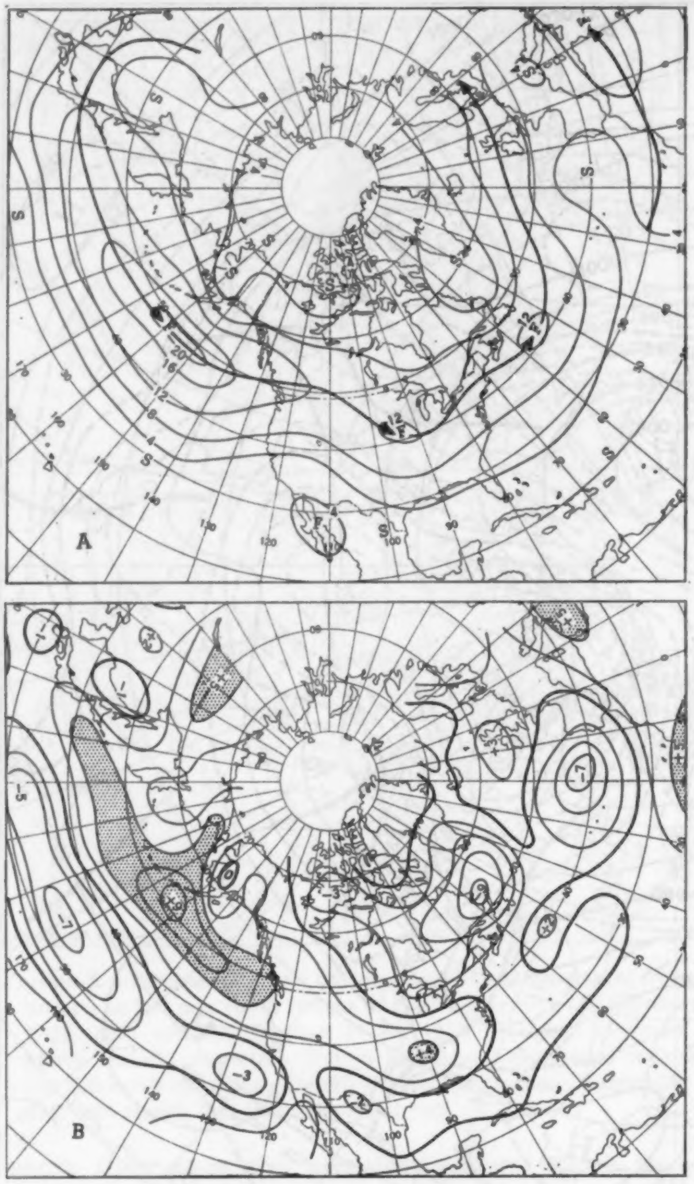

FIGURE 5.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for October 1955. Solid arrows in (A) indicate position of mean 700-mb. jet axes. The jet was strong and north of normal in the Pacific, weak and south of normal in the United States.

and parts of Utah and Arizona received no measurable precipitation. Heavy rains occurred in the Northwest as stronger than normal southwesterly flow of moist Pacific air crossed the mountain ranges. The mean trough in the eastern United States was accompanied by copious precipitation to its east. Considerable rain was also observed west of this trough. During the blocking periods, Gulf and Atlantic moisture curved cyclonically around the slow, northward moving daily Lows (Chart X), and precipitation fell well to the west of the cyclone centers. Early in the month, October 2–4, floods occurred

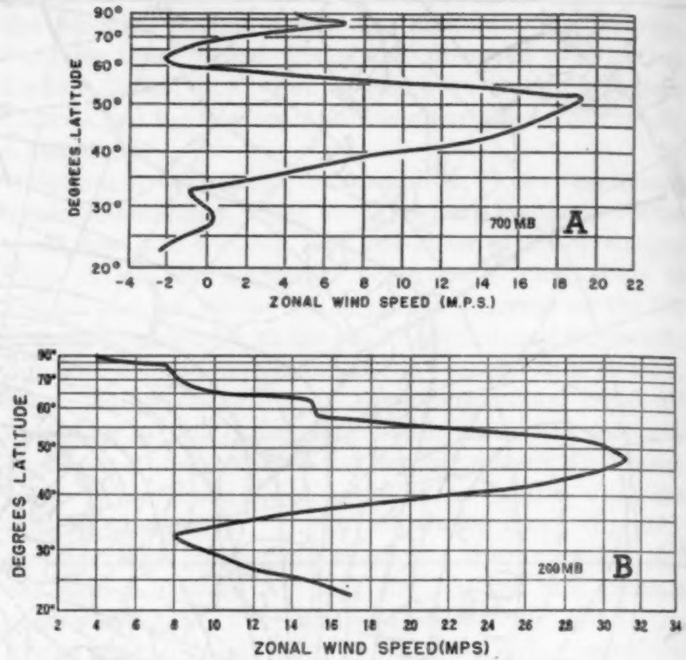

FIGURE 6.—(A) 700-mb. and (B) 200-mb. zonal wind speed profiles in the Western Hemisphere for October 9, 1955. Strong speeds and shears preceded the collapse of the westerlies.

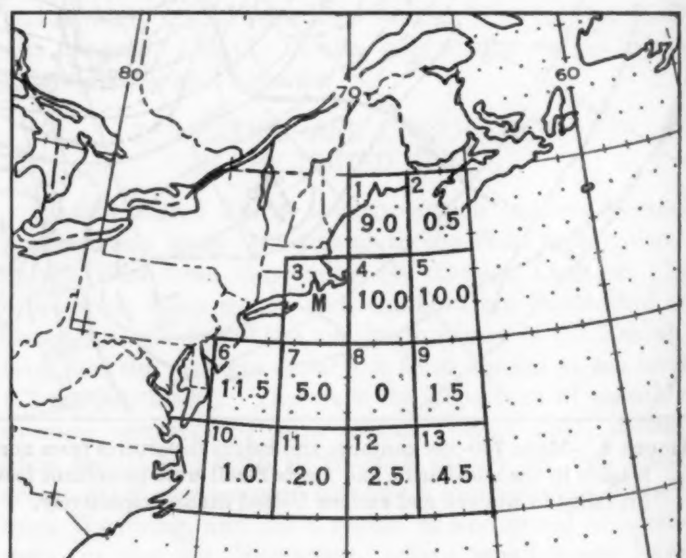

FIGURE 7.—Mean sea surface temperature departures from normal (to tenths of a degree F.) by 2½° squares for October 4–13, 1955. No observations were available in square numbered 3 (number in upper left hand corner). Anomalies were positive in all sectors and especially large along the coast.

in Oklahoma and heavy rain fell in parts of Texas as moist Gulf air masses replaced the cool air from the Pacific. Later, October 28 and 29, a cold front from the Pacific with its forerunning squall line produced severe thunderstorms and tornadoes in northern Louisiana and Mississippi.

Southern New England, and New York, which were still recovering from the August disaster [1] suffered another serious flood October 14–16. This October flood occurred during a period of strong blocking in eastern United States. A stagnant 700-mb. Low, blocked by a strong High to its northeast, was located west of Pennsylvania, and southerly, cyclonic flow favorable for heavy precipitation persisted over the flooded areas (see fig. 2B). (This situation has been treated in detail by Winner and Ross elsewhere in this issue.) Boston experienced its wettest October in 23 years, and Pittsfield, Mass., reported a new precipitation record, 7.04 inches, for this month.

In the August issue of this series [1] it was suggested that the anomalously warm ocean water off New England might have contributed to the extremely heavy rainfall associated with hurricanes Connie and Diane. Since this region again received copious rainfall, a spotcheck of the ocean-surface temperatures for the 10 days just prior to the floods was made in a manner similar to the August investigation. There were no negative anomalies observed, and near the coast temperatures were as much as 10° F. above normal, as shown in figure 7. Furthermore, during the entire period of heavy rain there was a strong easterly onshore flow over this warm water (see Daily Weather Maps for October 14–16, 1955).

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Weather Notes

(Continued from p. 224)

The Earl Bennett farm is located about 2½ miles north-northeast of the Post farm. Mr. Bennett was roused from bed between 10:05 and 10:10 p. m. Wednesday by hail, some as large as hen's eggs, which fell covering his yard. This was accompanied by severe and constant lightning. Then the storm struck, destroying several outbuildings. This was followed by a lull which lasted half a minute. Strong winds again struck suddenly (direction of winds unknown) but apparently with no further damage. Looking out to the north, Mr. Bennett saw the tornado funnel which was back-lighted by constant lightning farther to the north. He described the funnel as hanging down from a black cloud and gyrating slowly back and forth. He estimated it to be about a quarter of a mile in diameter in its lower portions. From the pattern of destruction of the Bennett farm it was not possible to deduce the direction of winds causing the damage. Debris which was carried as far as a mile to the north-northeast was relatively light in weight and was probably carried in the vortex.

Both of these accounts seem to indicate that the tornado funnel was on the trailing edge (south-southwest) of the parent thunderstorm itself, the parent thunderstorm being identified by the hail and severe lightning. Both accounts identified a quiet lull lasting for a minute or less between two storm surges suggestive of an "eye." In one case destruction occurred after the lull and in the other case before the lull. Neither eyewitness reported any sensation of change in pressure, having been questioned on that specific point. Both accounts indicated the absence of heavy rain accompanying the parent thunderstorm or the tornado, referring to the rain as "light."

Oxford, Kans.—A tornado struck just north of Oxford, Kans., about 2220 CST doing considerable damage, completely destroying several sets of farm buildings and killing five children from one family. Little information of meteorological significance is available from this area. One witness reported an automobile going "straight up" and being deposited eastward several hundred yards from its initial position.

Udall, Kans.—Udall, Kans., about 30 miles southeast of Wichita, underwent almost complete destruction from the tornado which struck about 2235 CST. Motorists were reported to have seen the tornado funnel approaching Udall. It struck the southwest corner of the town first, traveling almost due northeast with destruction occurring over the entire width of the town, about three-fourths of a mile. The only habitable structure left in town was a frame dwelling with only minor damage on the extreme northwest edge of town. Except for a few other dwellings in the northwest corner of town which were twisted, moved, and badly damaged, the only buildings in town not completely leveled were a few two-story masonry buildings from which the upper story had been removed. There was evidence of rotation although it was confused somewhat by the pattern of light-weight debris, much of which indicated a southwest to northeast flow. It was not uncommon, for instance, to see a large tree having fallen to the southwest, and a large piece of tin wrapped around a smaller nearby tree with its free edges pointing northeastward, obviously having been carried by a southwest wind. Destruction requiring immense forces however did yield indications of cyclonic rotation. A municipal water tower in the northwest part of town was toppled toward the southwest. The center of rotation passed across and at almost right angles to a train of railroad cars on a railroad siding. The cars to the northwest of the center were blown off the tracks to the southwest and the cars to the southeast of the center were blown to the northeast, although some cars between (over a distance of about 1½ city blocks) were still on the tracks.

Some evidence was found of "explosive" effects. A concrete block building about 30 feet by 40 feet stood in the southwest part of town and was apparently near the path of the center of the tornado. All four walls had fallen outward, leaving the floor area relatively clear of debris.

Eyewitness accounts were not available from Udall until several days afterward because of understandable confusion and the shock that most survivors suffered. Wheeler Martin, a survivor from Udall, reported that there was a "roaring noise" at about 2220 CST followed by hail and rain. The wind was from the southwest and getting stronger. After a few minutes, the house began to shake. At 2235 CST it "collapsed." The hail continued for several minutes.

FIGURE 1.—General location map for Blackwell, Okla.-Udall, Kans., tornadoes, May 25, 1955.

Beyond Udall, the path of major destruction ended. Spotty damage extended for 18 miles east-northeast of Udall.

A carefully conducted survey of damage accomplished by one of the authors Mr. Phillips revealed almost positive indications that at least from the time the tornado crossed U. S. Highway 166 and throughout its northward traverse through Udall, a continuous path of destruction was apparent. There was some "skipping" but the greatest skip was on the order of 3½ miles.—*Victor V. Phillips, MIC, WBAS, Wichita, Kans.; Joseph G. Galway, SELS Center, Kansas City, Mo.; and Donald M. Hanson, District Forecast Center, Kansas City, Mo.*

SYNOPTIC FEATURES ATTENDING THE HEAVY RAINS IN THE MIDDLE ATLANTIC STATES AND SOUTHERN NEW ENGLAND, OCTOBER 13-17, 1955

J. P. WINNER AND R. B. ROSS

National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

1. INTRODUCTION

The storm of October 13–17, 1955, which brought heavy rains to the Middle Atlantic States and produced floods, notably in southern New England, is of major interest following so closely the disastrous August floods in New England in the wake of hurricane Diane. Although the heavy rains and floods with the October storm were not as catastrophic as with Diane, they reached major proportions in the same, heavily populated, industrial area not yet recovered from the earlier floods [1, 2].

It is proposed in this article to illustrate this storm, showing the features contributing to the situation and to discuss some of the mechanisms which produced the heavy rains. Of primary interest, is the blocking feature that existed at the time and the deep moisture emanating as it did from a cyclonic development off the east coast of Florida.

2. SURFACE FEATURES

On October 12, 1955 an area of below normal pressure formed over Cuba and its adjacent waters. This depression remained in relatively the same position until it was dissipated on October 15, 1955, with the passage of a cold front moving through the area from the northwest. On October 13, 1955, a center of low pressure formed to the north of this depression in a position approximately 125 nautical miles to the east of Daytona Beach, Fla. (fig. 1). This low deepened and moved to the northeast in advance of a trough of low pressure. This trough extended southeastward from a stagnating Low located in Canada to the north of the Great Lakes. By 1230 GMT, October 14, the Atlantic Coast Low was centered about 60 nautical miles northeast of Cape Hatteras, N. C., and had a central pressure of 995 mb. At this point the Low was moving into an area of increasing southeasterly flow and it recurved toward the northwest moving up the Delaware Bay and through central Pennsylvania. By 1230 GMT, October 15 the Low had moved into extreme southern Ontario, Canada, where it stalled and filled.

The rain area was clearly identified with the system of fronts which existed during the storm (figs. 1, 2). A persistent High in the Labrador region was attended by an extensive flow of polar air moving southward and westward across the Canadian Maritime Provinces. This flow maintained a sharp front separating the tropical and polar air. The front remained stationary just south of Long Island and thus provided a persisting lifting mechanism. Meanwhile the dry polar air to the west advanced steadily southeastward across Florida and the Bahamas, but in the Northeastern States the advance was slowed by the easterly flow attending the blocking High. This led to an occluded system which provided an excellent upslope structure that remained nearly stationary over the area of heavy rains. The easterly flow was further strengthened by the intensification and retrogressive movement of a cyclone to the southeast of the blocking High (fig. 1).

3. THE HEAVY RAIN AREA

The largest amounts of rain fell in western Massachusetts, western Connecticut, and southeastern New York (fig. 2). Point rainfall amounts in the above area were as great as 15 inches for the storm. Heavy rain fell over a large additional area which included southern New England, most of New York, central and eastern Pennsylvania, New Jersey, Maryland, and much of eastern Virginia.

4. THE MOISTURE PATTERNS

An analysis of the moisture patterns which occurred during the storm clearly showed the source region as the tropical Atlantic Ocean in the general vicinity of the Bahama Islands. Precipitable water amounts for the period of the storm were computed, following Solot and Showalter [3, 4], for available radiosonde data at 0300 GMT and 1500 GMT. The isopleths of precipitable water for each 0.50-inch interval were then transferred to the corresponding surface charts (fig. 1). From these charts it is seen that the moist tongue moved northward and in advance of the small Low which originated off the Florida East Coast. Further, that the moisture was carried strongly northward and northwestward into the

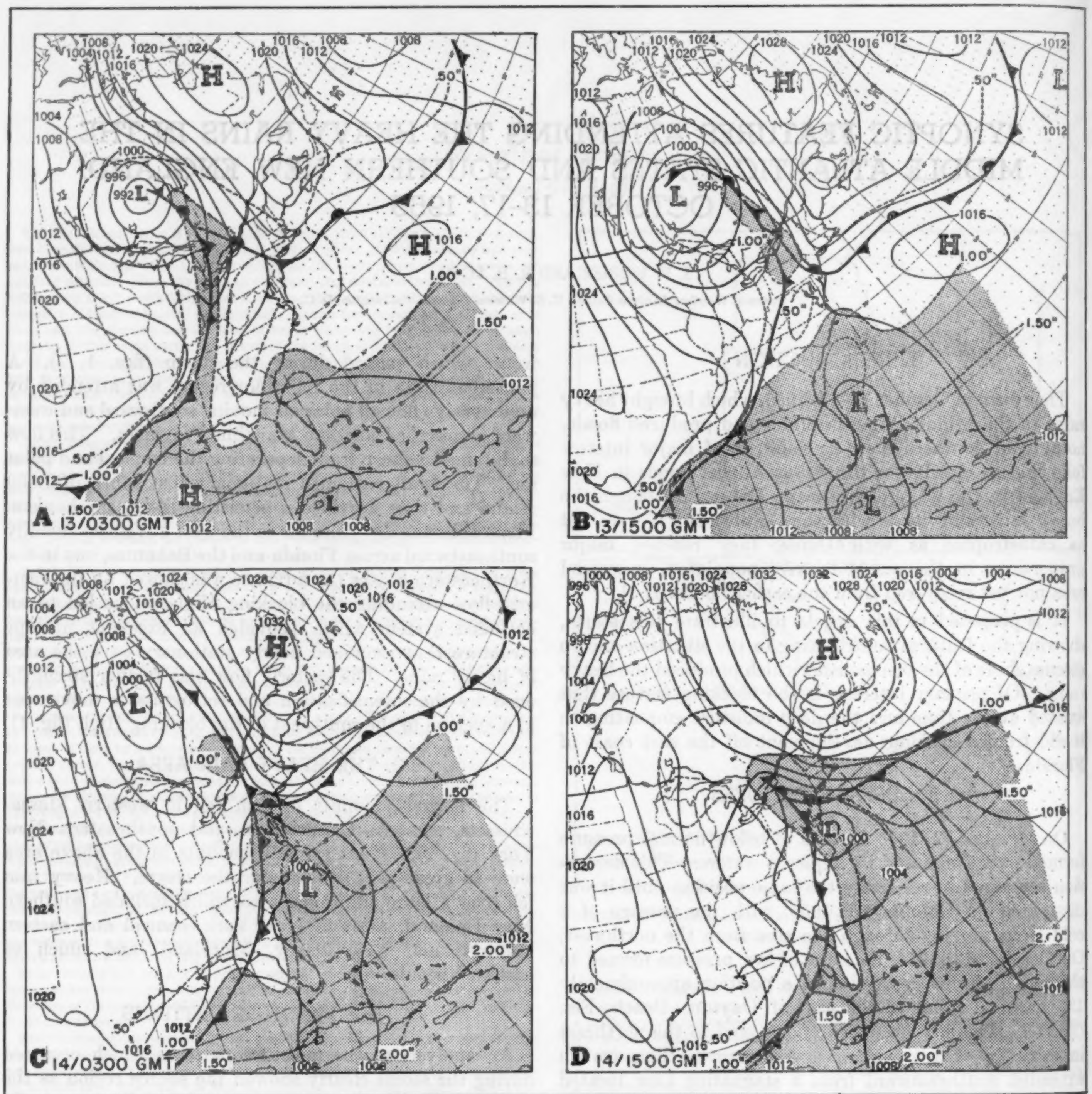

FIGURE 1.—Surface charts at 12-hour intervals 0330 GMT and 1530 GMT, October 13–16, 1955. Isopleths of precipitable water (dashed lines) with an interval of 0.50-inch are superimposed. Shaded areas indicate 1 inch or more of precipitable water. Note the northward progress of moisture associated with the Atlantic Coast Low into the region of the occluded front.

occluded frontal structure for an extended period of time. It also seems reasonable to conclude that the nature of the circulation attending the low pressure system, which had many tropical characteristics, insured favorable conditions for the production of heavy rain. At 1500 GMT, October 15, the computed precipitable water at Hempstead, N. Y., was 1.86 inches. This value, although less than the maximum of record observed for the station [5], is comparable to the mean value occurring in southern Florida in October. The moist tongue was carried northwestward by the strong flow aloft resulting in heavy rain as far west as Buffalo, N. Y.

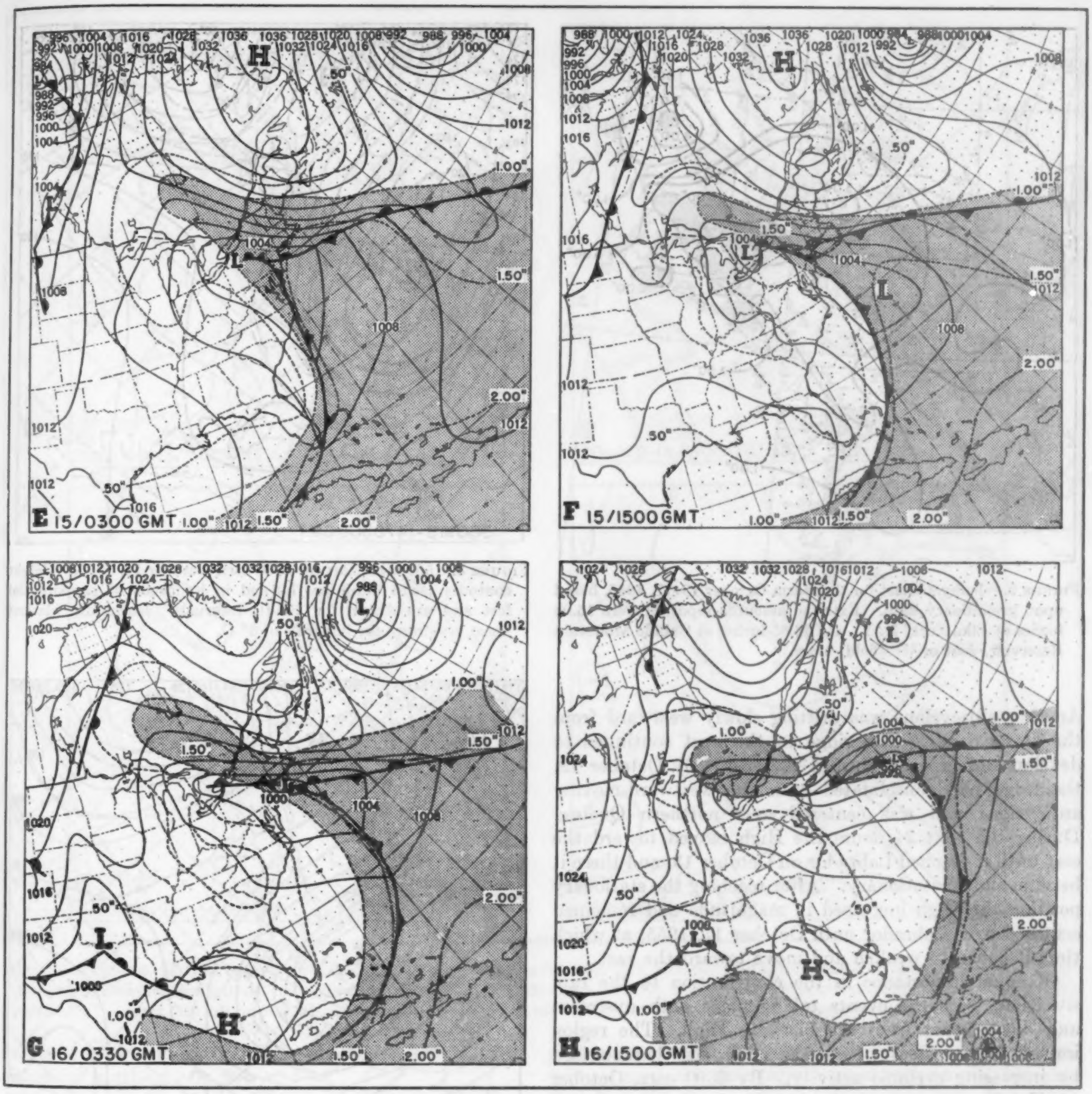

FIGURE 1—Continued.

5. UPPER AIR FEATURES

The period October 13–17 was characterized by strong southerly to southeasterly flow at all tropospheric levels over the region of heavy precipitation. This flow was associated with the broad-scale upper air features persisting throughout the period. A strong blocking High was centered over Labrador as evidenced at the surface and the 500-mb. levels (figs. 1, 3, 4). At the 500-mb. level on October 11, 1955 a large anticyclone was centered over Tennessee and northern Georgia. A developing ridge extended northward from the High to Hudson Bay.

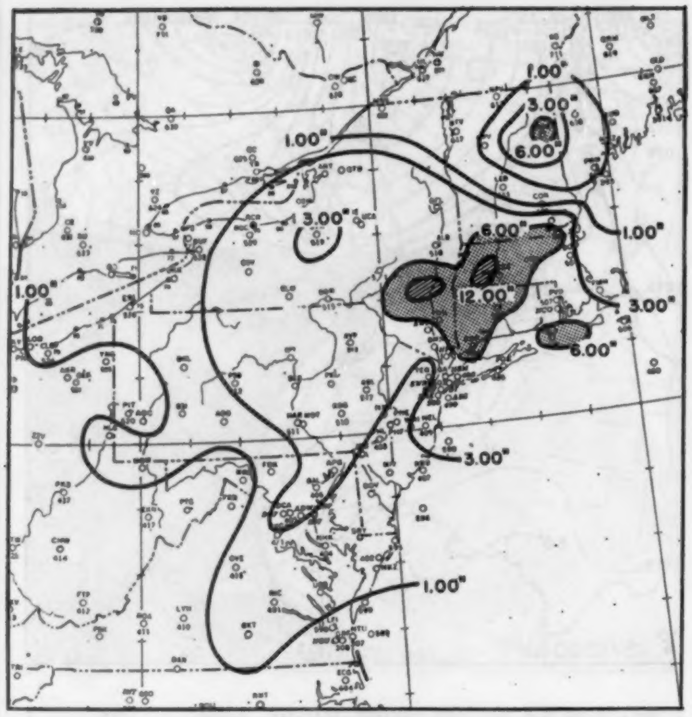

Figure 2.—Isohyet chart for the storm October 13–17, 1955, based upon preliminary data. Extreme amounts reported were 15.03 inches at Elka Park, N. Y., and 13.85 inches at Cobble Mountain Reservoir, west of Westfield, Mass.

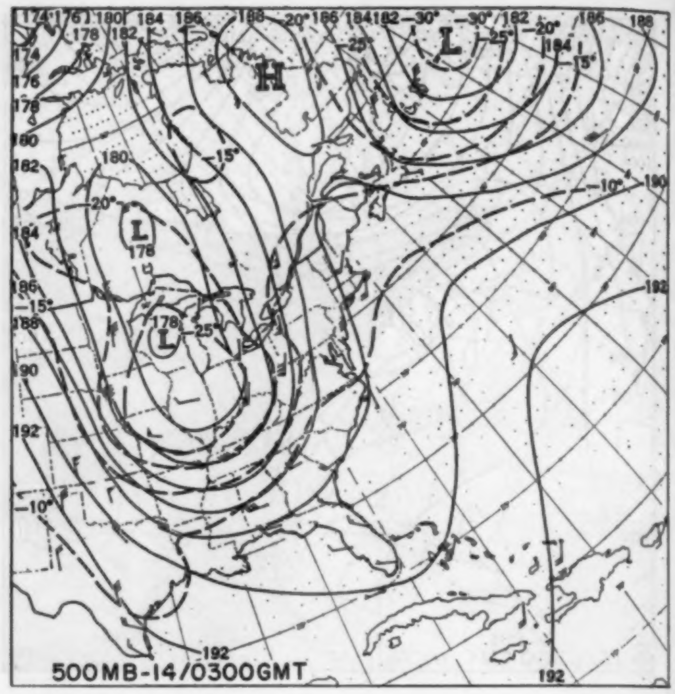

Figure 3. 500-mb. chart for 0300 GMT, October 14, 1955. Height contours (solid lines) are labeled in hundreds of geopotential feet and are drawn for 200-ft. intervals. Isotherms (dashed lines) are drawn for intervals of 5° C.

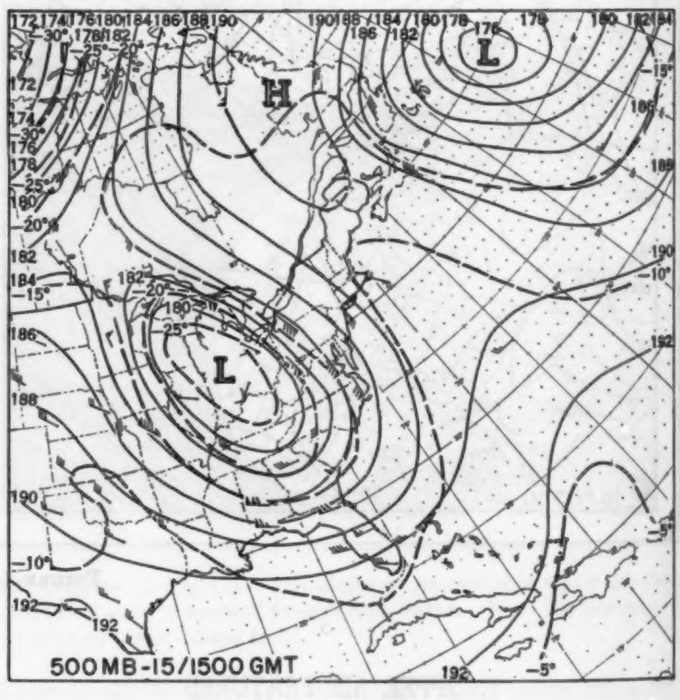

Figure 4.—500-mb. chart for 1500 GMT, October 15, 1955.

Another anticyclone was drifting slowly westward from the Davis Strait. The ridge to the west continued to develop and progress toward the east. By October 12, the ridge had consolidated with the westward-moving anticyclone and was centered over northern Quebec. During the next 24 hours the High moved toward the east until it reached Labrador on October 13, and there it became almost stationary. After reaching the stationary position the High increased in magnitude and remained centered over Labrador until October 17, 1955, at which time it began to weaken and move toward the east.

Of equal importance in the contribution to the rain situation, were the events taking place both upstream and downstream from the blocking High. The region immediately upstream from the High was characterized by increasing cyclonic activity. By 0300 GMT, October 14 (fig. 3), a trough at the 500-mb. level was oriented north-south extending from northern Canada to the Gulf of Mexico. In this trough an elongated cut-off Low, having a double center, extended from the southern portion of Hudson Bay to southern Illinois. One center of this Low was located southeast of Trout Lake, Ontario, and the other center was located to the west of Green Bay, Wis. A short-wave-length trough associated with the Atlantic Coast Low extended from Wilmington, N. C., to Cuba. By 1500 GMT, October 15 (fig. 4), the Low at 500 mb. was centered near Toledo, Ohio, with a trough oriented northwest-southeast. A zone of strong southsoutheasterly flow extended from the Carolinas into Canada. The axis of the trough line continued to back as the flow on the rear side of the trough became more westerly, with the axis of the trough line assuming more and more of a west-east orientation. By October 16,

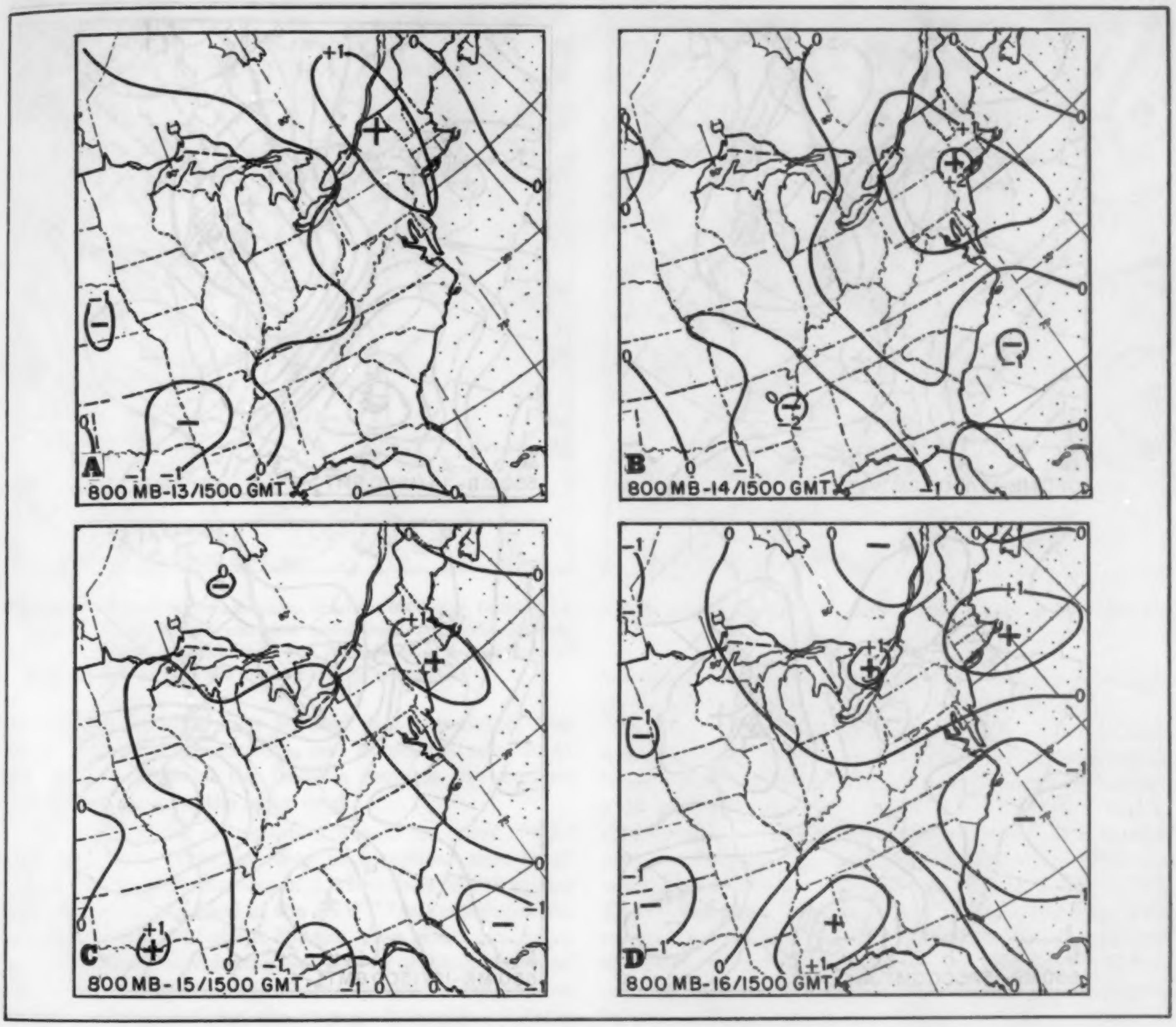

Figure 5.—800-mb. vertical velocity (W) charts at 24-hour intervals for 1500 GMT, October 13–16, 1955 based on data furnished by Joint Numerical Weather Prediction Unit. Contours are labeled in units of cm. sec.$^{-1}$. The vertical velocity values are mean instantaneous values for the layer 900 mb. to 700 mb. Positive values indicate ascending motion and negative values, descending motion.

the area of maximum rainfall was under the zone of maximum southeasterly flow aloft.

The region immediately downstream from the blocking High was also characterized by increasing cyclonic activity. A cut-off Low formed in a trough at 500 mb. east of Newfoundland near 41° N., 42° W. This Low developed very rapidly and moved toward the west. For an account of the mean, broad-scale features of the flow during October 1955, the reader is referred to the article by Dunn [6] elsewhere in this issue.

6. VERTICAL MOTION

The subject of numerical prediction of precipitation is presently receiving much attention [7]. The field of vertical motion is an integral part of such predictions and, therefore, is being presented here as a synoptic feature.

Analyses of the mean, large-scale vertical velocities have been prepared from data furnished by the Joint Numerical Weather Prediction Unit. The computed vertical velocities are mean "instantaneous" [1] values for a specific layer. In the case of the vertical motion illustrated by the 800-mb. W chart (fig. 5) the layer extends from 900 mb. to 700 mb. Values shown on the 550-mb. W chart (fig. 6)

[1] "Instantaneous" is used here in a relative sense. The computed values of vertical velocities are mean values over a period of 1 hour centered 30 minutes after the time of the synoptic upper air data. This time period is inherent in the machine method of computation.

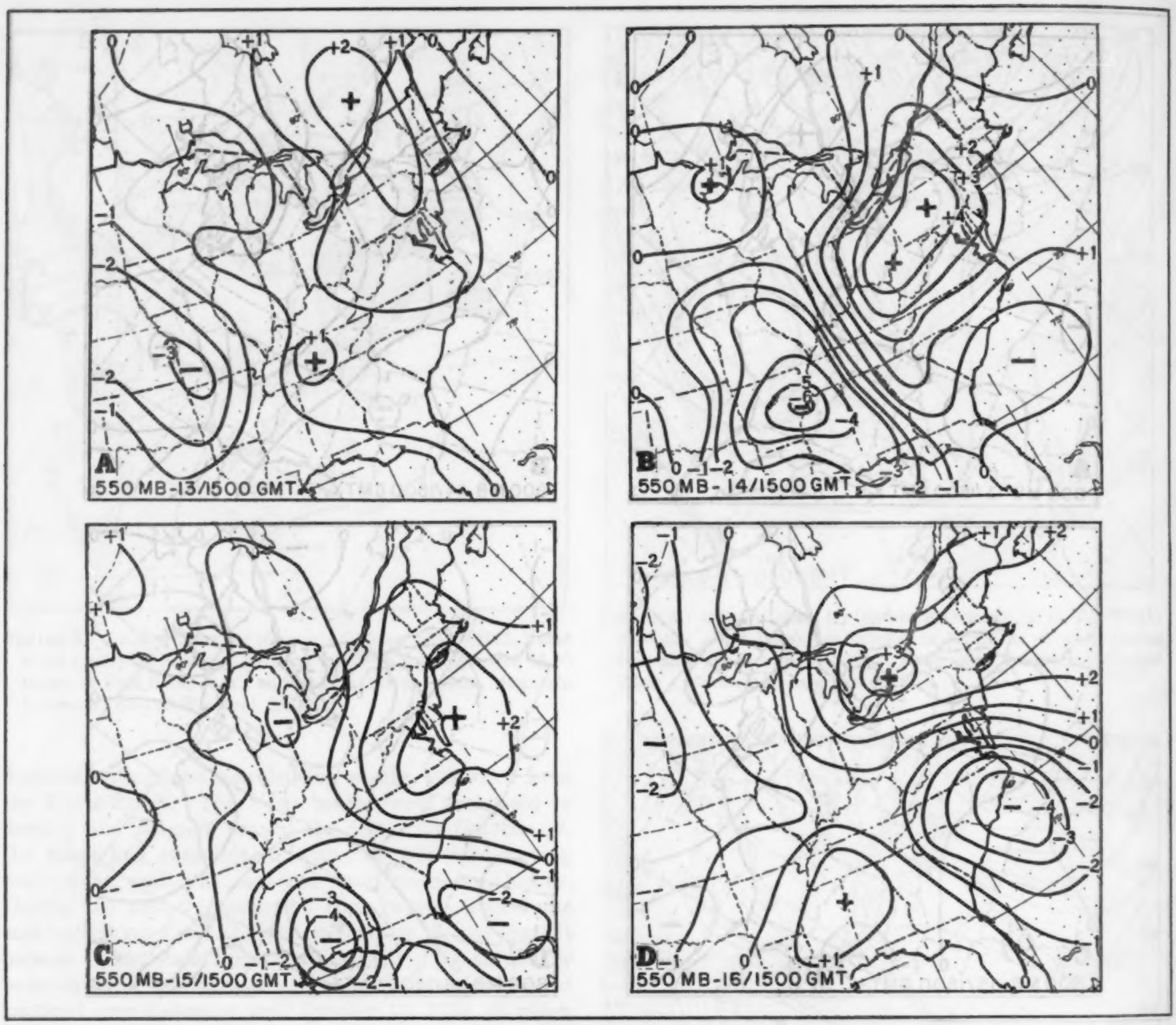

FIGURE 6.—550-mb. vertical velocity (W) charts at 24-hour intervals for 1500 GMT, October 13–16, 1955 based on data furnished by Joint Numerical Weather Prediction Unit. The vertical velocity values are mean instantaneous values for the layer 700 mb. to 400 mb.

apply to the layer between 700 mb. and 400 mb. Comparison of the charts of vertical velocities with the rainfall and precipitable water charts (figs. 1, 2) shows good qualitative agreement between the area of heavy rainfall and the location of positive vertical motion of very moist air. Quantitative interpretation requires consideration of the grid size used in the computation of the vertical motion and of the local convective and orographic effects.

Following Showalter [8] a computation of rainfall intensity was made using a vertical velocity of 2 cm. sec.$^{-1}$ and substituting other reasonable values in his formula. Showalter's formula for computing point rainfall intensity is

$$I=\frac{W\rho_0(w_0-w_1)}{7}$$

Where I=intensity of rainfall over unit area, in./hr.
W=vertical velocity at condensation level, m. p. s.
ρ_0=air density at condensation level, grams/m.^{3}
w_0=mixing ratio at condensation level, grams/gram
w_1=mixing ratio at top of convective updraft, grams/gram

The Showalter formula assumes the product $\rho_0 W$ to be constant throughout the lifting process; in other words, there is no convergence or divergence. If convergence is

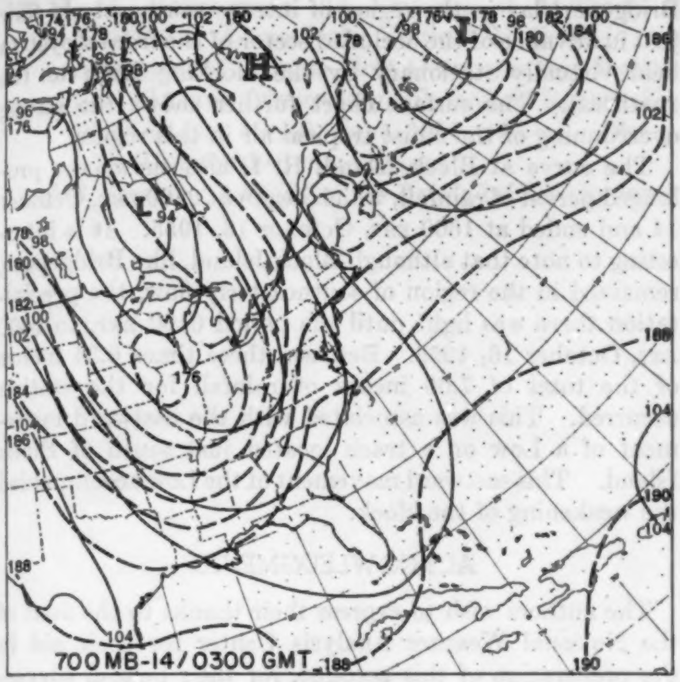

FIGURE 7.—Temperature advection chart for 0300 GMT, October 14, 1955. 700-mb. height contours (solid lines) and 1000–500-mb. thickness lines (dashed lines) are both labeled in hundreds of geopotential feet and are drawn for intervals of 200 ft.

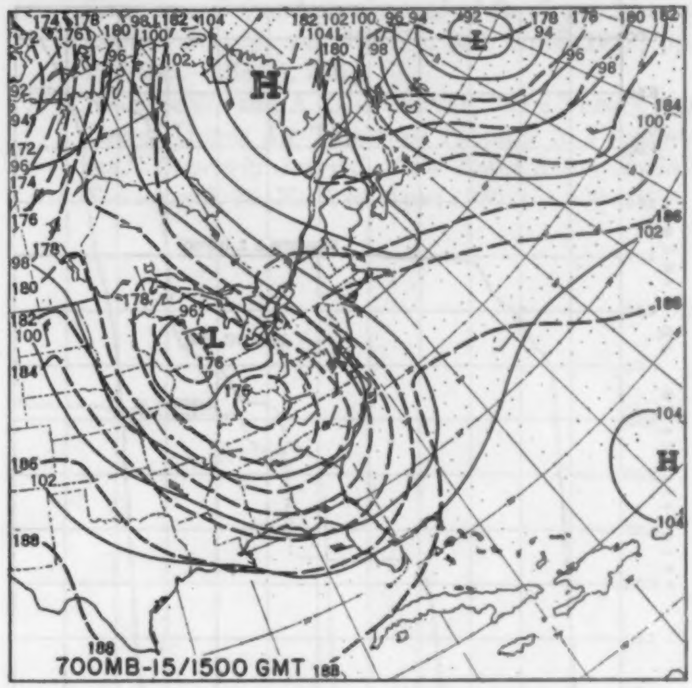

FIGURE 8.—Temperature advection chart for 1500 GMT, October 15, 1955.

present the formula must be used in a cumulative step basis. In any computation ρ_0 and W must be selected at the same level since the formula requires the product $\rho_0 W$ be constant for the layer used.

The result of the computation was of the order of 0.05 inch per hour. This intensity as computed here is, of course, applicable to an area of not less than 35,000 square miles since the grid used in the JNWP Unit computations is a square lattice of about 300 km. on a side. As shown by Showalter's "enveloping isohyets of greatest observed depth" [8], point rainfall intensities would be expected to amount to several times the average intensity occurring over an area of several thousand square miles. Also, as pointed out by other authors [7, 9, 10, 11] the effects of local convection and of orographic lifting would not necessarily be revealed by the large-scale field of vertical velocity.

7. WARM ADVECTION

Warm geostrophic advection was a prominent synoptic aspect over the area of heavy rain. In order to illustrate this feature the mean temperature pattern (1000–500-mb. thickness) has been superimposed upon the corresponding 700-mb. contour chart (figs. 7, 8). As can be seen by inspection, warm advection was at a maximum from about Chesapeake Bay to southeastern New York and western Connecticut at 0300 GMT, October 14. By 1500 GMT, October 15, this feature was still at a maximum over western Connecticut and southeastern New York and had become quite prominent in central and eastern New York where large amounts of rain occurred (fig. 2).

It is noteworthy, that in northern Maine, where rainfall was negligible, cold advection is apparent on both charts. During the 36-hour period 0300 GMT, October 14 through 1500 GMT, October 15, as can be seen in figures 7 and 8, the 18,400-ft. thickness line advanced about 360 nautical miles, or at a rate of about 10 kt. The mean advective wind during the same period was approximately 30 kt. The excess of 20 kt. probably was resolved into large-scale vertical motion. However, because of the complicated relationships between vertical motion and cooling [12] of unstable air it is very difficult to establish a quantitative balance of these factors.

8. OROGRAPHY

The orographic influence with this storm cannot be overlooked. The stations reporting extreme amounts of precipitation were all located at relatively high elevations; for instance, Elka Park, N. Y., which reported 15.03 inches, is high in the Catskill Mountains (elev. 2,250 ft. m. s. l.) and Cobble Mountain Reservoir, west of Westfield, Mass., is in the Berkshire Mountains (elev. approx. 1,000 ft. m. s. l.). It is also interesting to note that Mount Washington, N. H., which was well to the northeast of the area of heaviest precipitation reported 6.31 inches.

9. PRECIPITATION MASS CURVES

The history of this storm can be dramatically summarized by an examination of the precipitation graphs

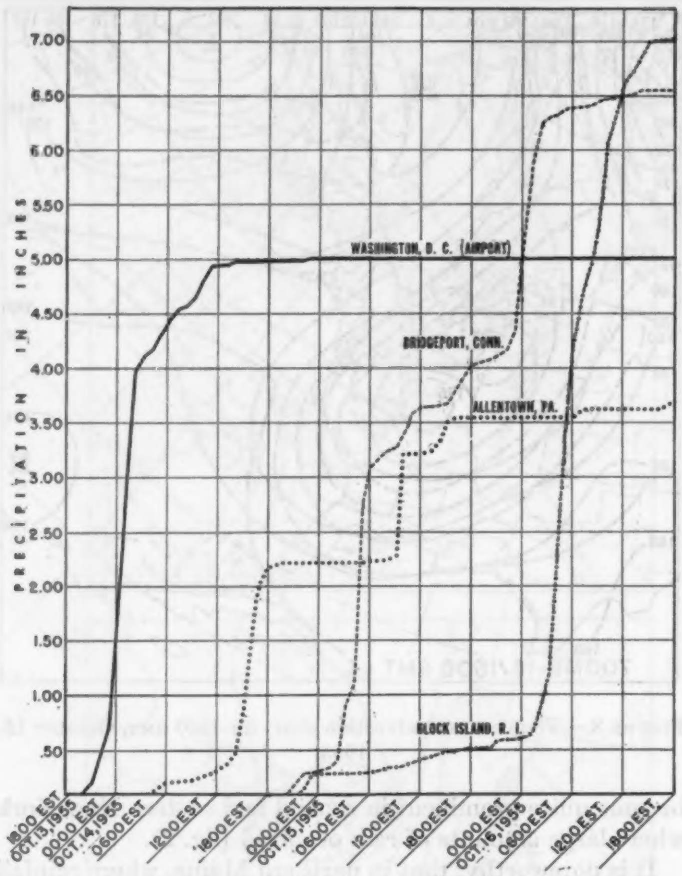

FIGURE 9.—Precipitation graph (mass curves) October 13–17, 1955 for selected stations. Data based upon hourly precipitation amounts as taken from monthly station summaries.

(mass curves) for Washington, D. C., Allentown, Pa., Bridgeport, Conn., and Block Island, R. I. (fig. 9), making cross-reference to the surface charts (fig. 1). The mass precipitation curve for Washington, D. C. shows that a total of 5 inches of rain fell, 3 inches of which fell in one burst between 2300 EST, October 13, and 0200 EST, October 14, 1955. The heavy rainfall at Washington occurred simultaneously with the passage of the cold front moving from the west and the arrival of the deep moist tropical air moving northward with, and in advance of, the Atlantic Coast Low. The rain at Washington was accompanied by intense thunderstorm activity reflecting the unstable conditions in existence at the time.

The mass curve for Allentown, Pa. shows that the total precipitation occurred in two bursts. The first burst between 1400 and 1800 EST, October 14, 1955 occurred with the passage of the Atlantic Coast Low as it moved inland and directly over the station. The second burst, occurring between 0900 and 1000 EST, October 15, accompanied the passage of the cold front.

The curve for Bridgeport, Conn., shows sustained and heavy rainfall throughout most of the period beginning at 2000 EST, October 14 and ending at 1400 EST, October 16. An examination of the surface charts shows that Bridgeport lay in the region of intense southeasterly flow just in advance of the occluded sector of the frontal system held virtually stationary by the blocking High to the northeast. The surface chart further shows the strong overrunning of the moist tropical air in this region.

The curve at Block Island, R. I. also shows the prolonged period of rainfall, which began at 2100 EST, October 14 and ended at 1600 EST, October 16, 1955. It is interesting to note that although Block Island, like Bridgeport, remained in the region of southeasterly flow, the precipitation there was light until the period 0100 EST, to 1400 EST, October 16, 1955. Between these times 6.34 inches of the total of 7.00 inches of rainfall for the station occurred. This was associated with the eastward movement of a Low on a track located just south of Block Island. This eastward movement of the Low accompanied the weakening of the block.

ACKNOWLEDGMENTS

The authors wish to express their thanks to the staff of the National Weather Analysis Center for their aid in the preparation of this account, for their helpful suggestions and constructive criticism. We are also indebted to the staff of the Daily Map Unit who prepared the illustrations.

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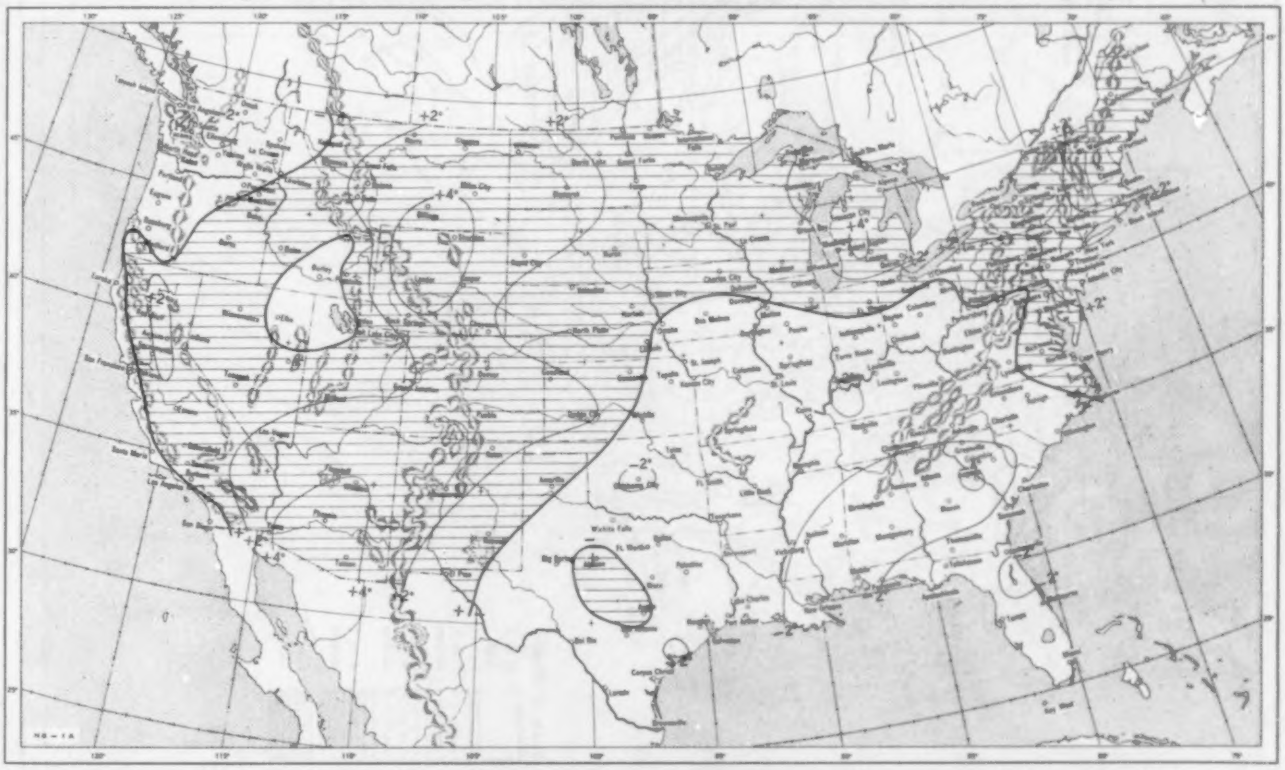
Chart I. A. Average Temperature (°F.) at Surface, October 1955.

B. Departure of Average Temperature from Normal (°F.), October 1955.



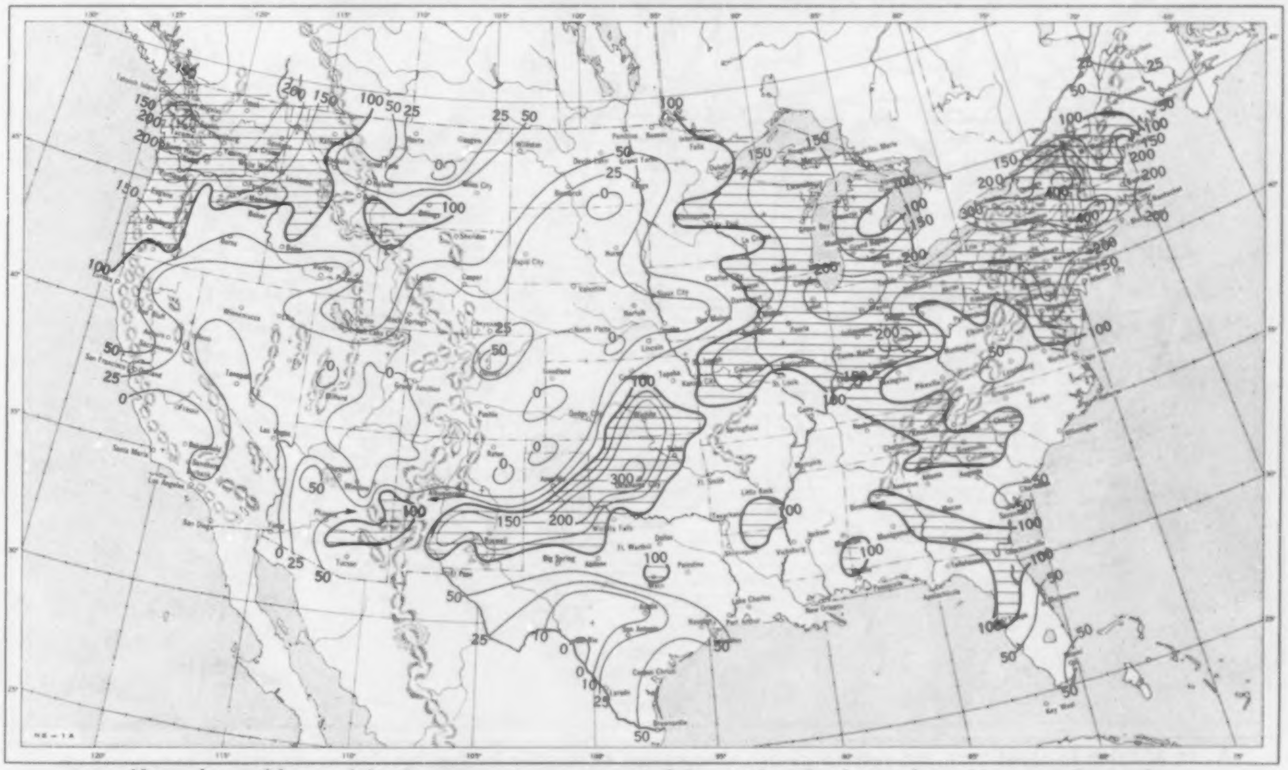
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), October 1955.

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

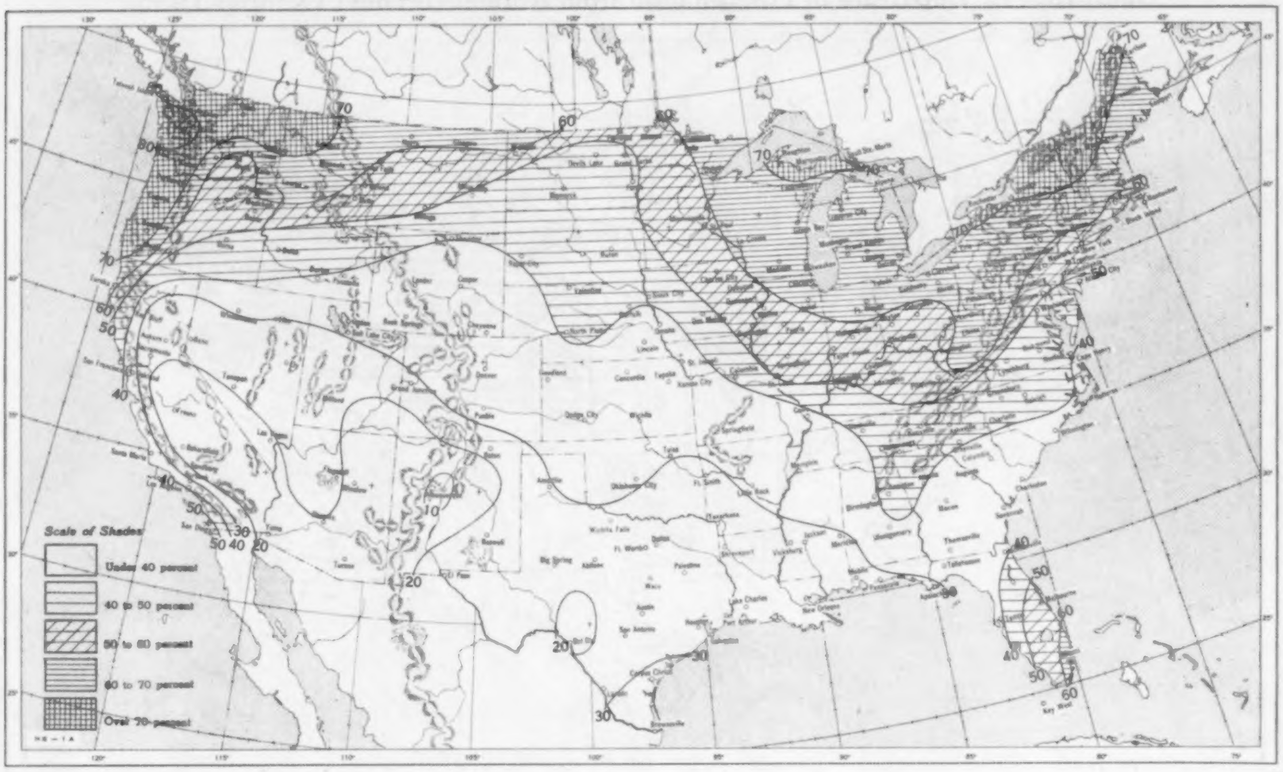
Chart III. A. Departure of Precipitation from Normal (Inches), October 1955.

B. Percentage of Normal Precipitation, October 1955.

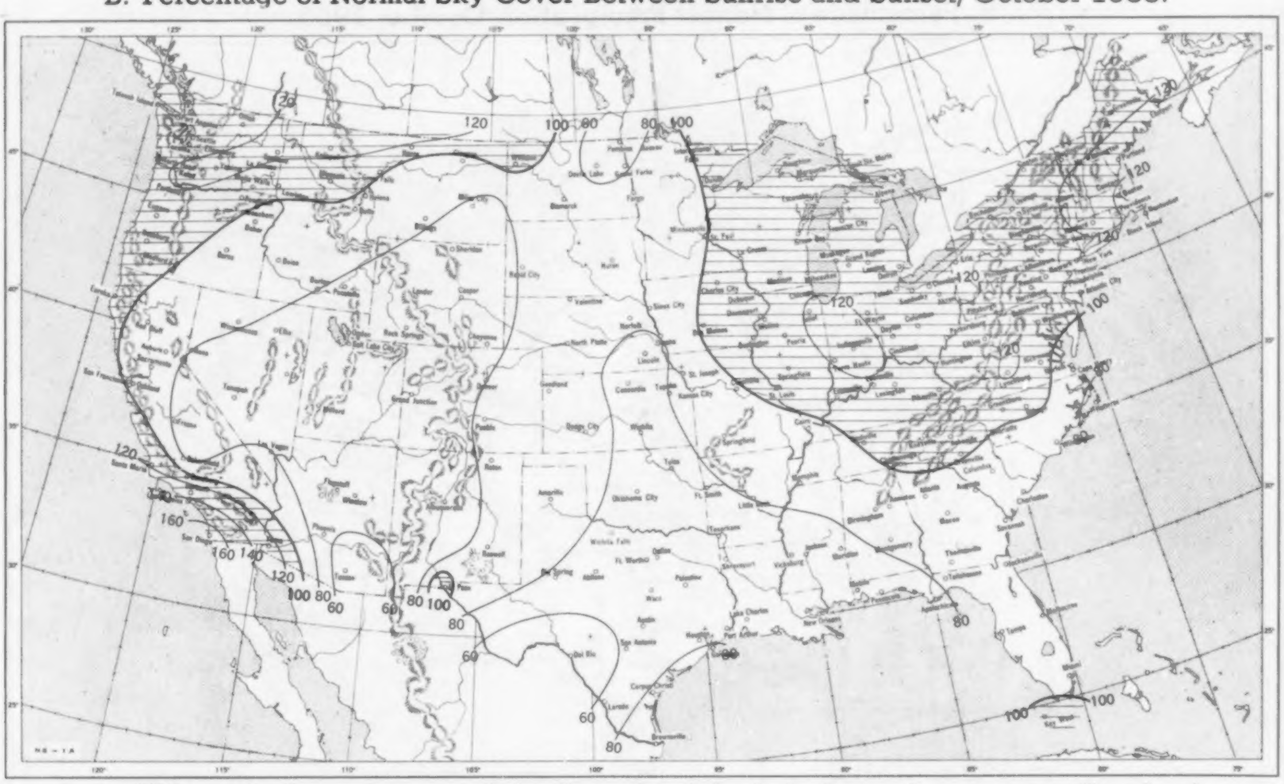


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, October 1955.

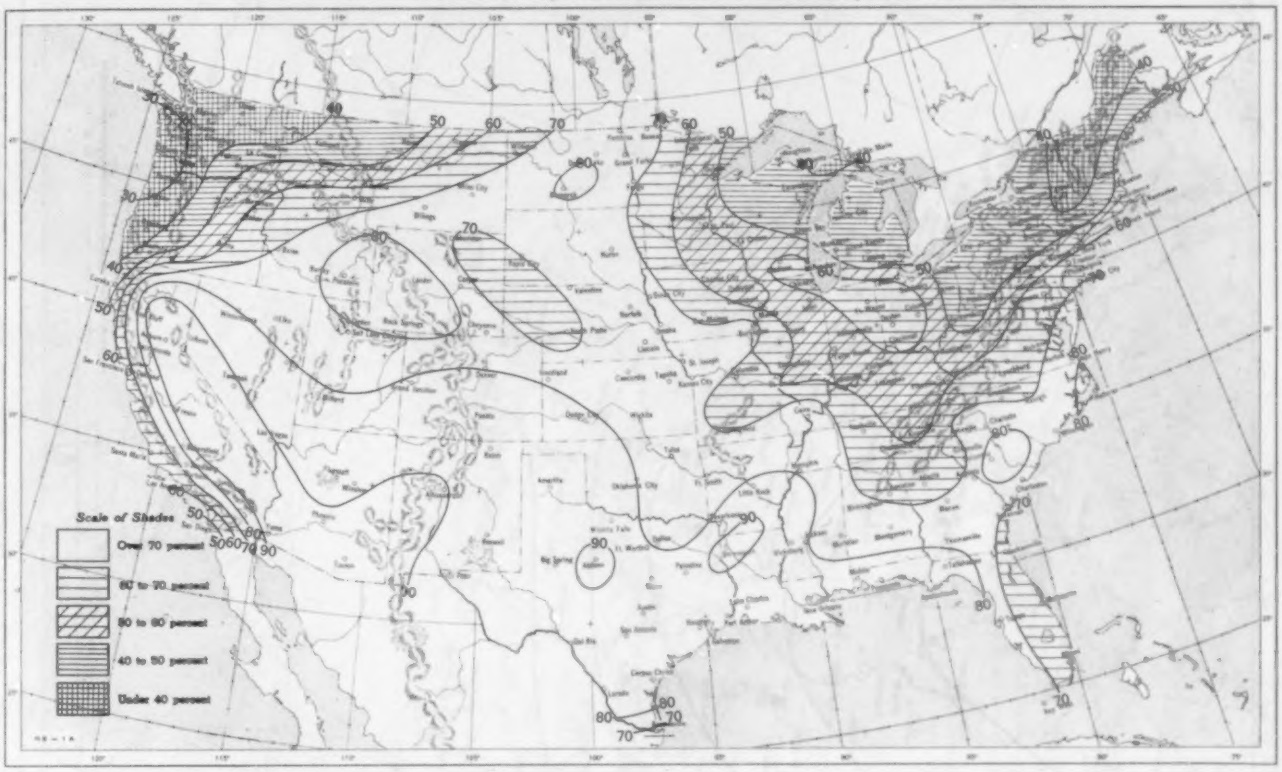


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, October 1955.

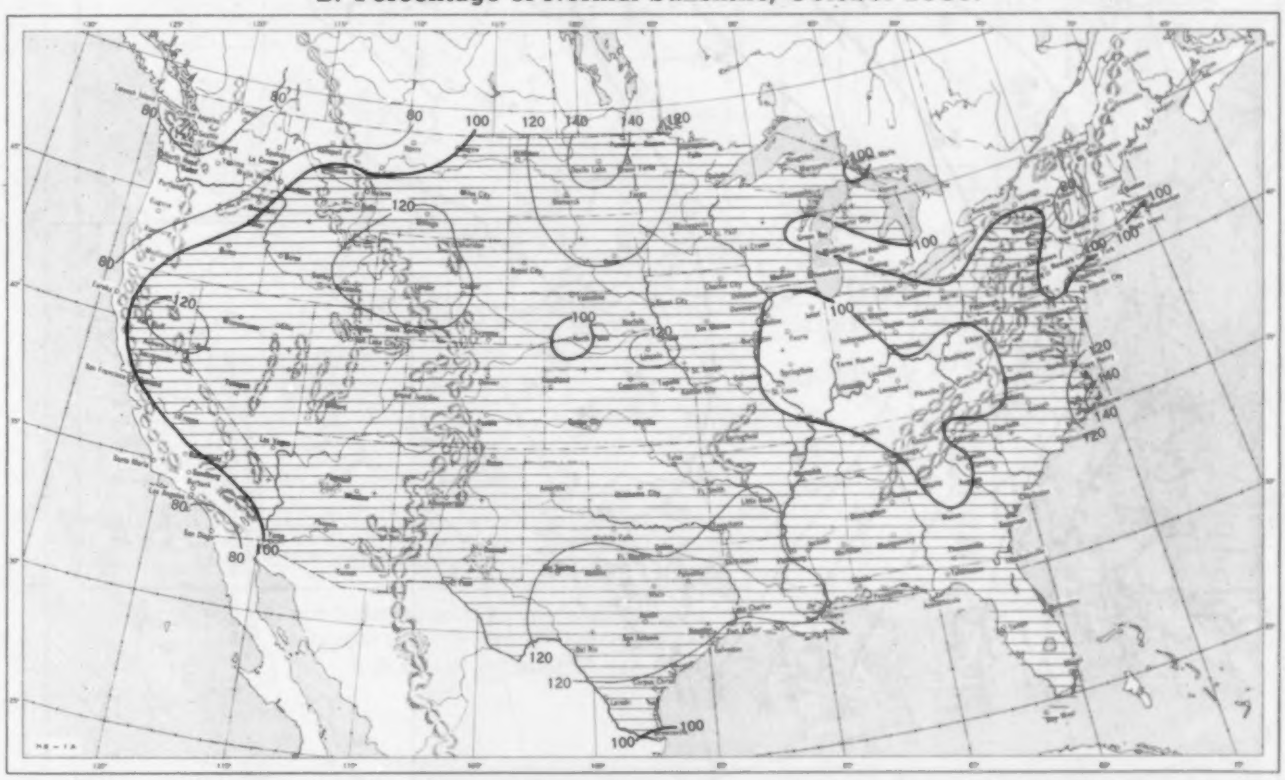


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, October 1955.



B. Percentage of Normal Sunshine, October 1955.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, October 1955. Inset: Percentage of Normal Average Daily Solar Radiation.

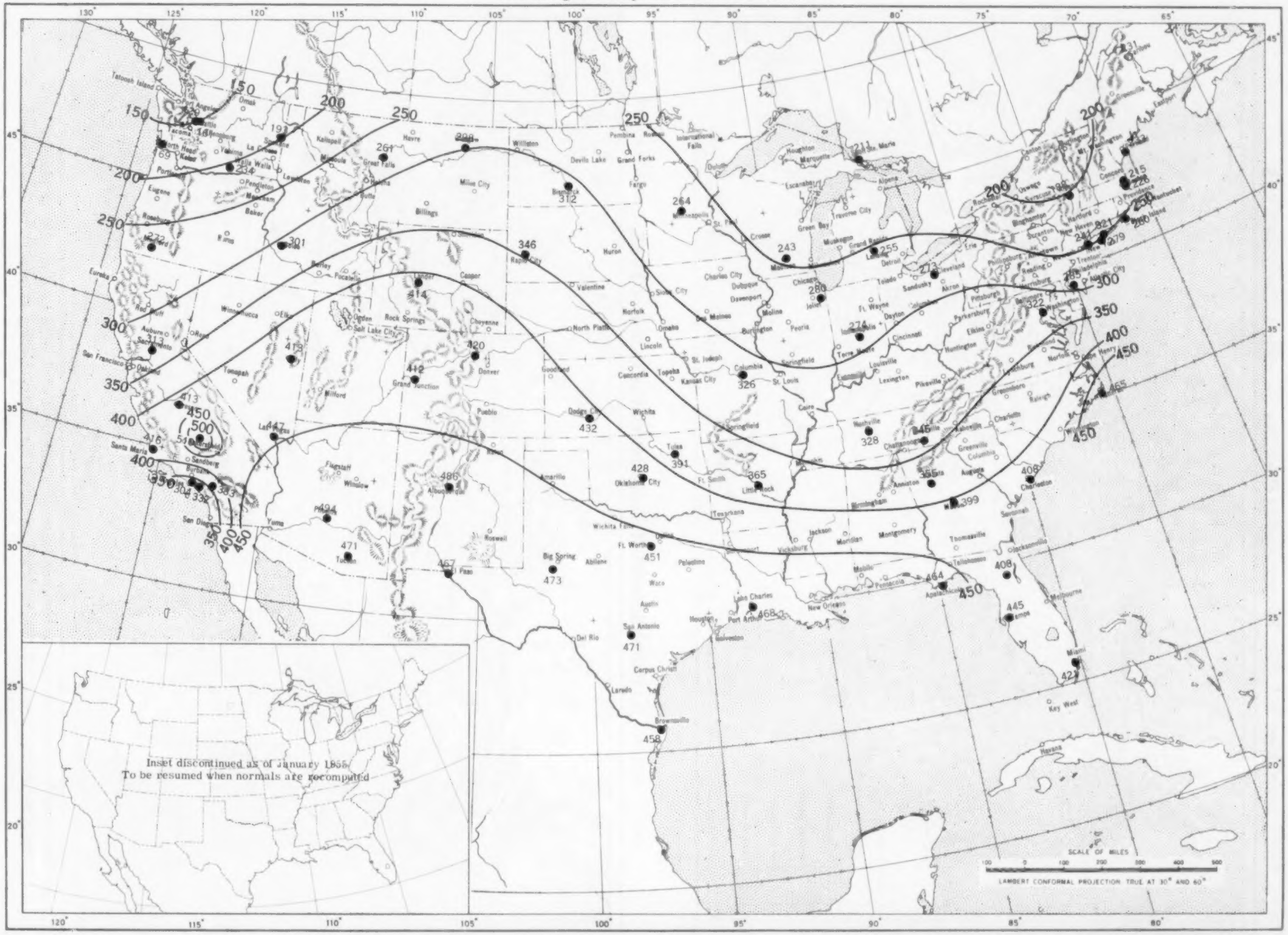
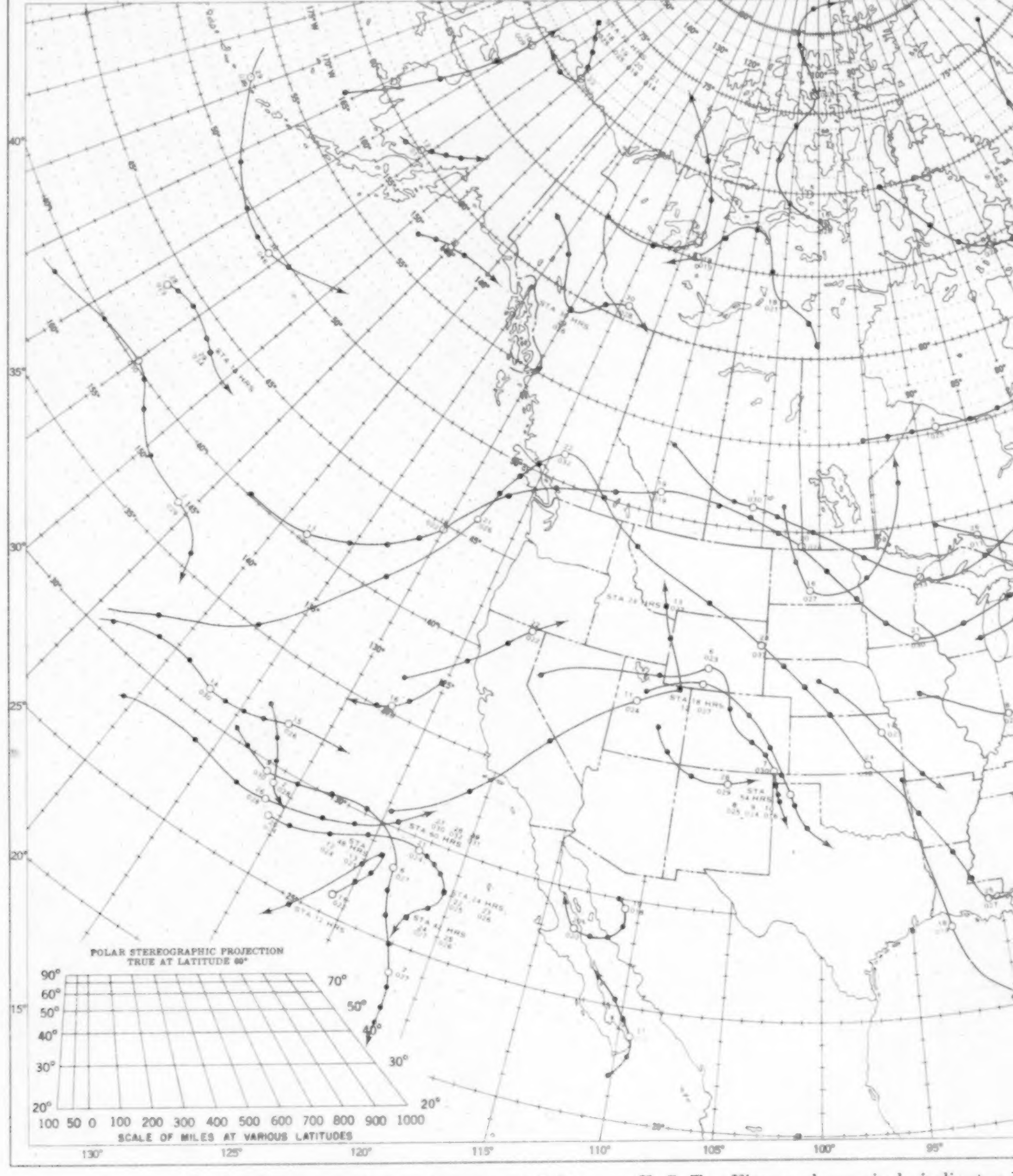


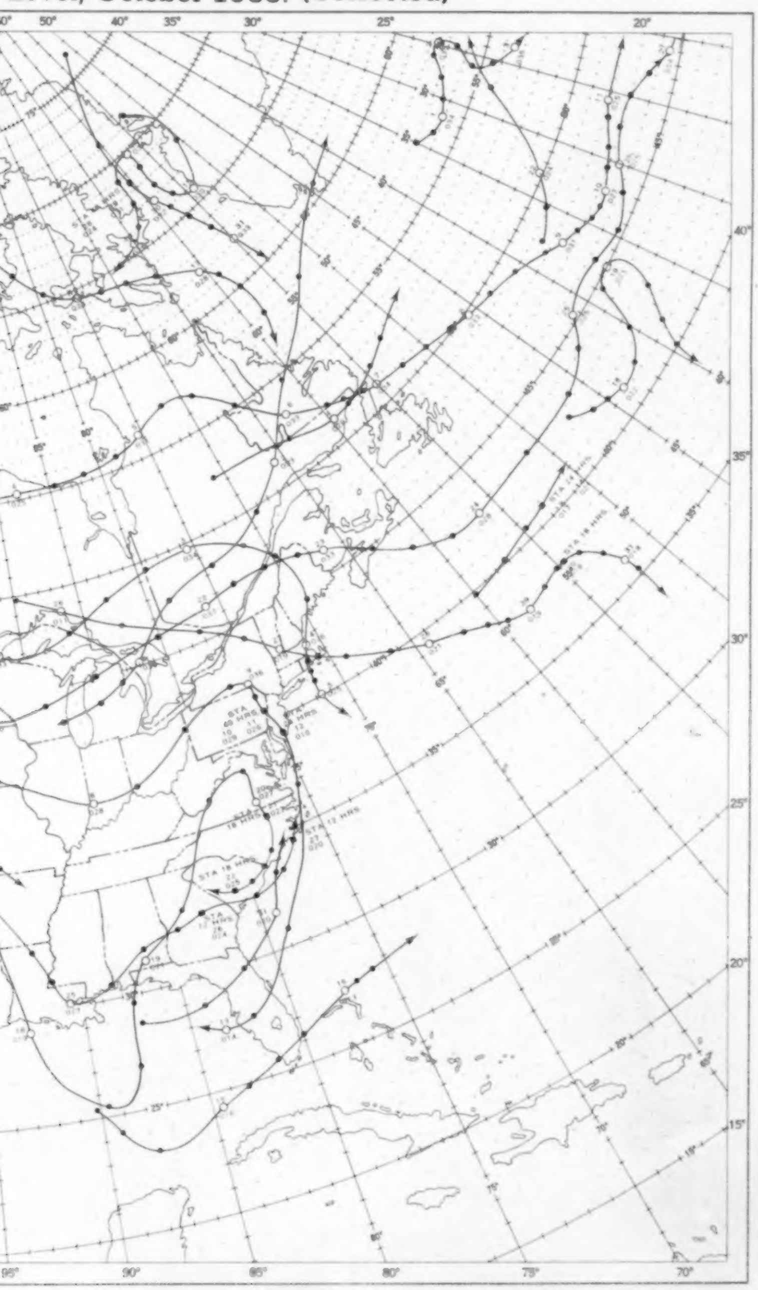
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, C



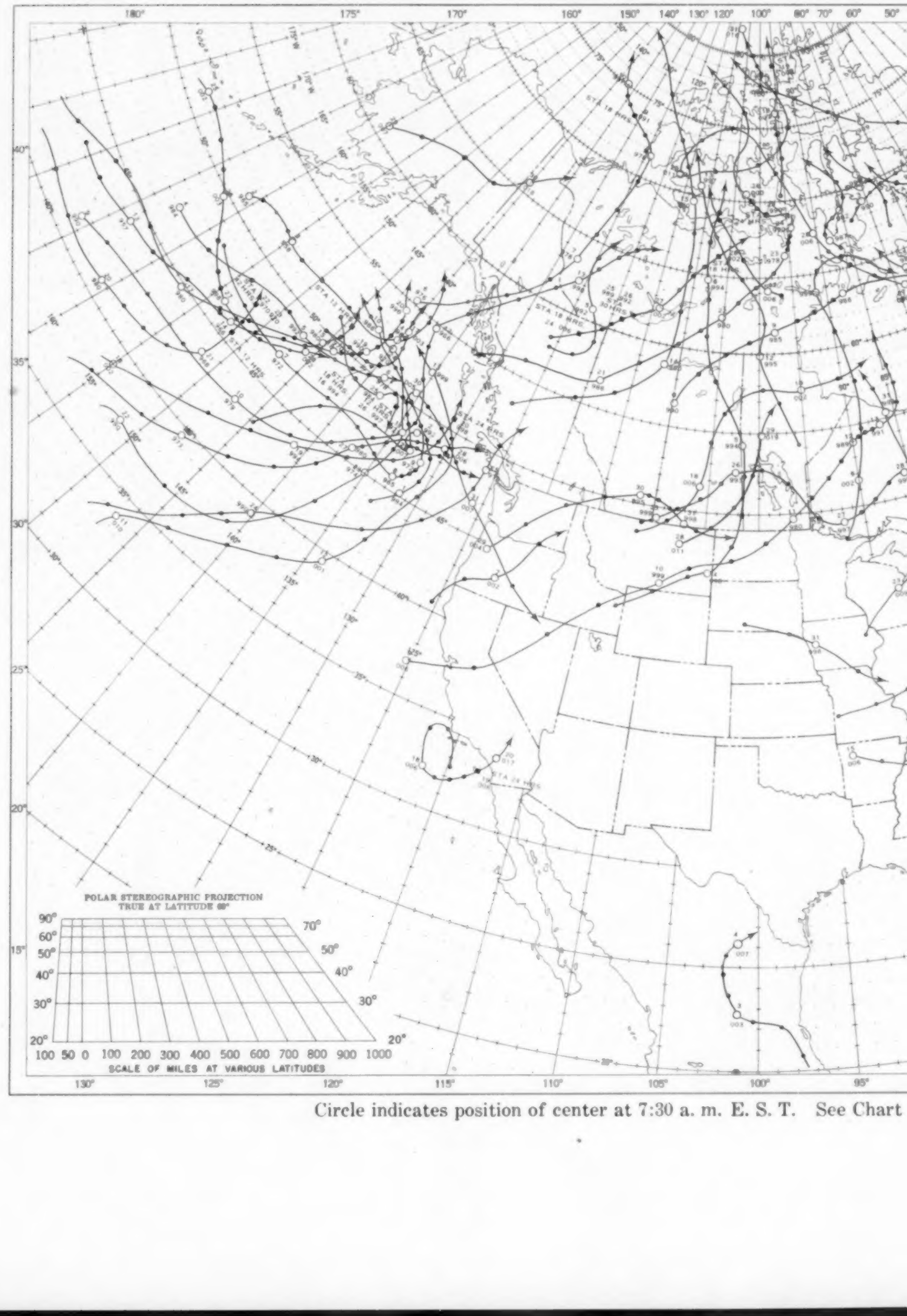
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates d
Dots indicate intervening 6-hourly positions. Squares indicate position of stationary c
indicates reformation at new position. Only those centers which could be iden

Level, October 1955. **(Corrected)**



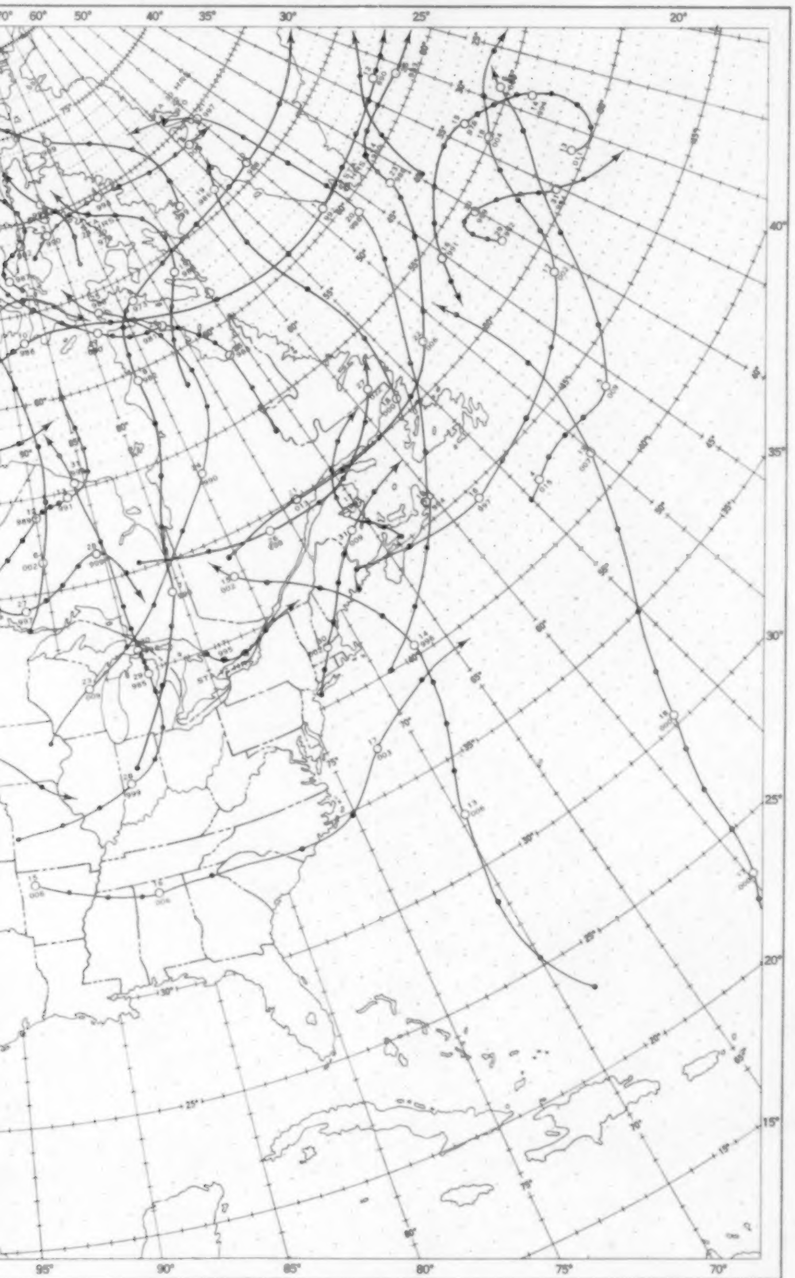
ndicates date, figure below, pressure to nearest millibar.
ationary center for period shown. Dashed line in track
d be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, (



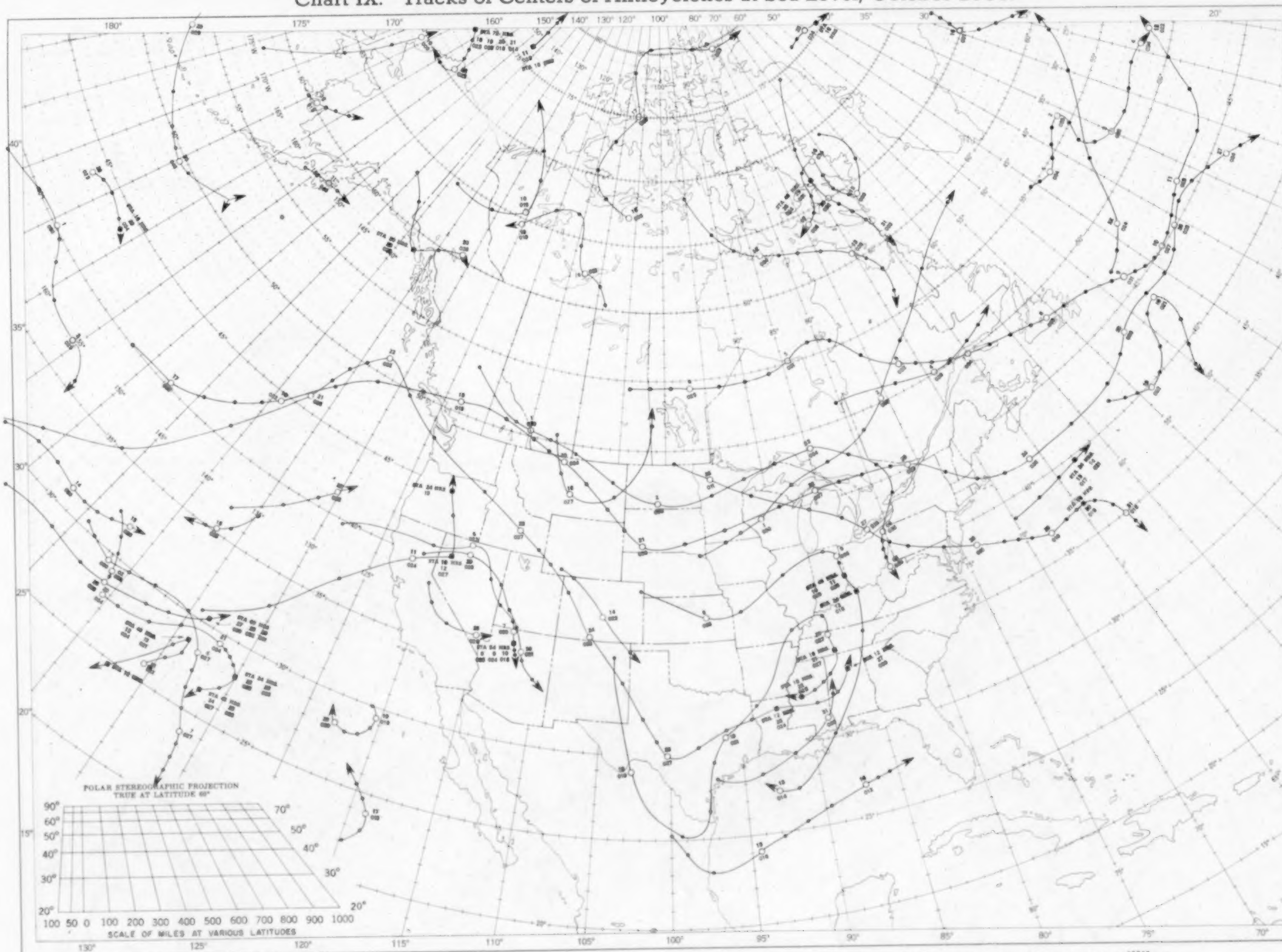
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart

Level, October 1955. (Corrected)



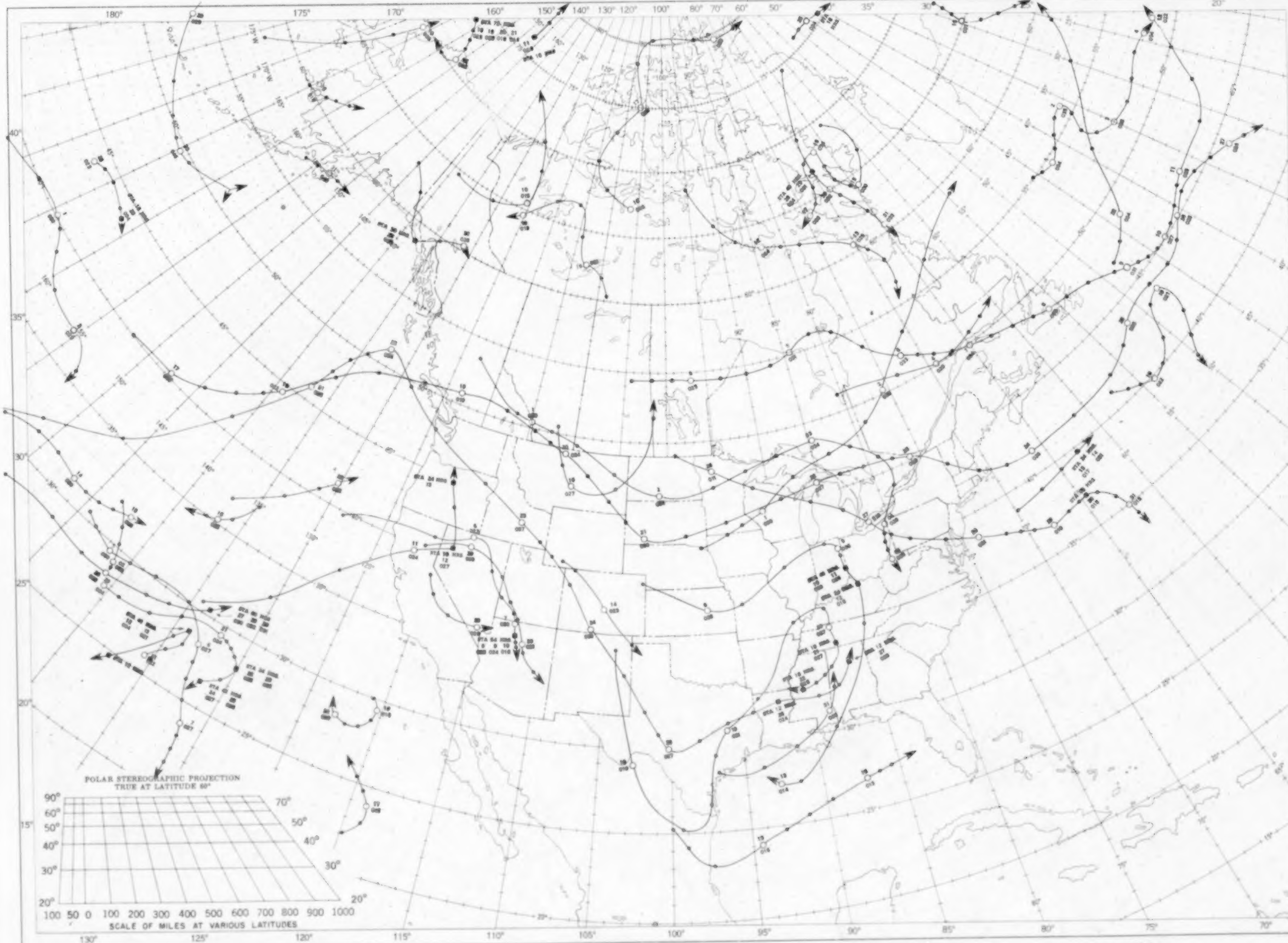
See Chart IX for explanation of symbols.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, October 1955.



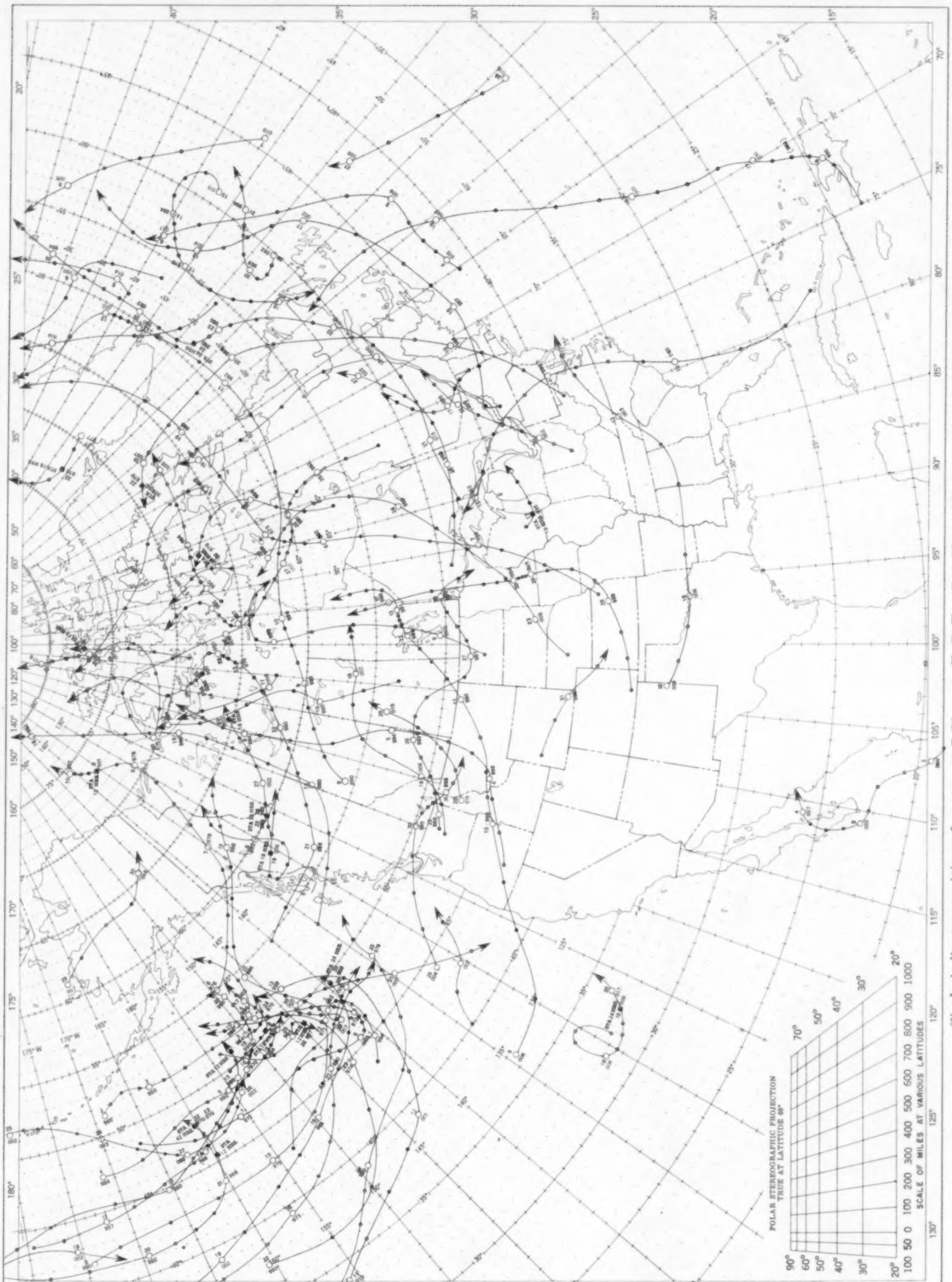
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, October 1955.



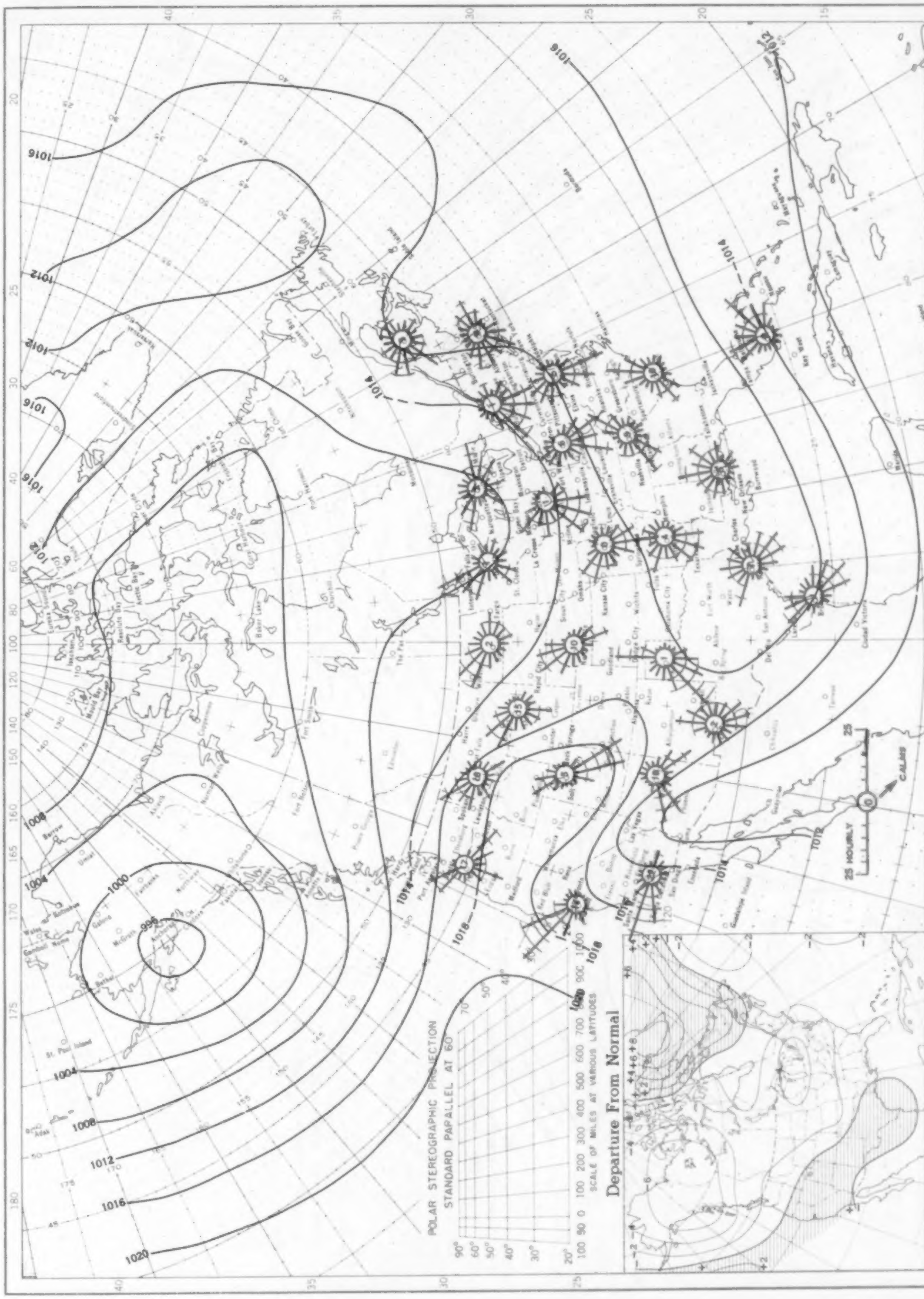
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, October 1955.



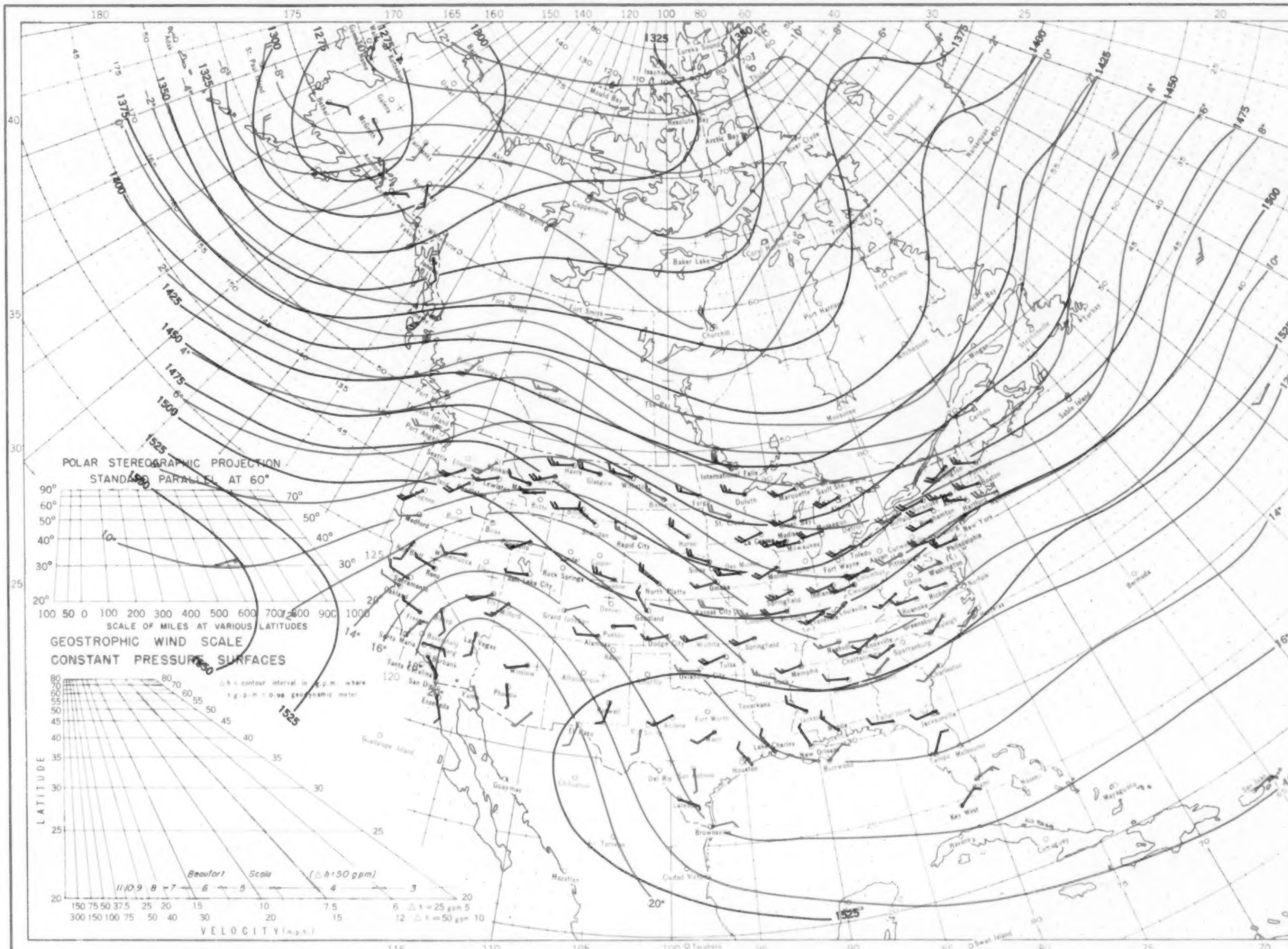
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, October 1955. Inset: Departure of Average Pressure (mb.) from Normal, October 1955.



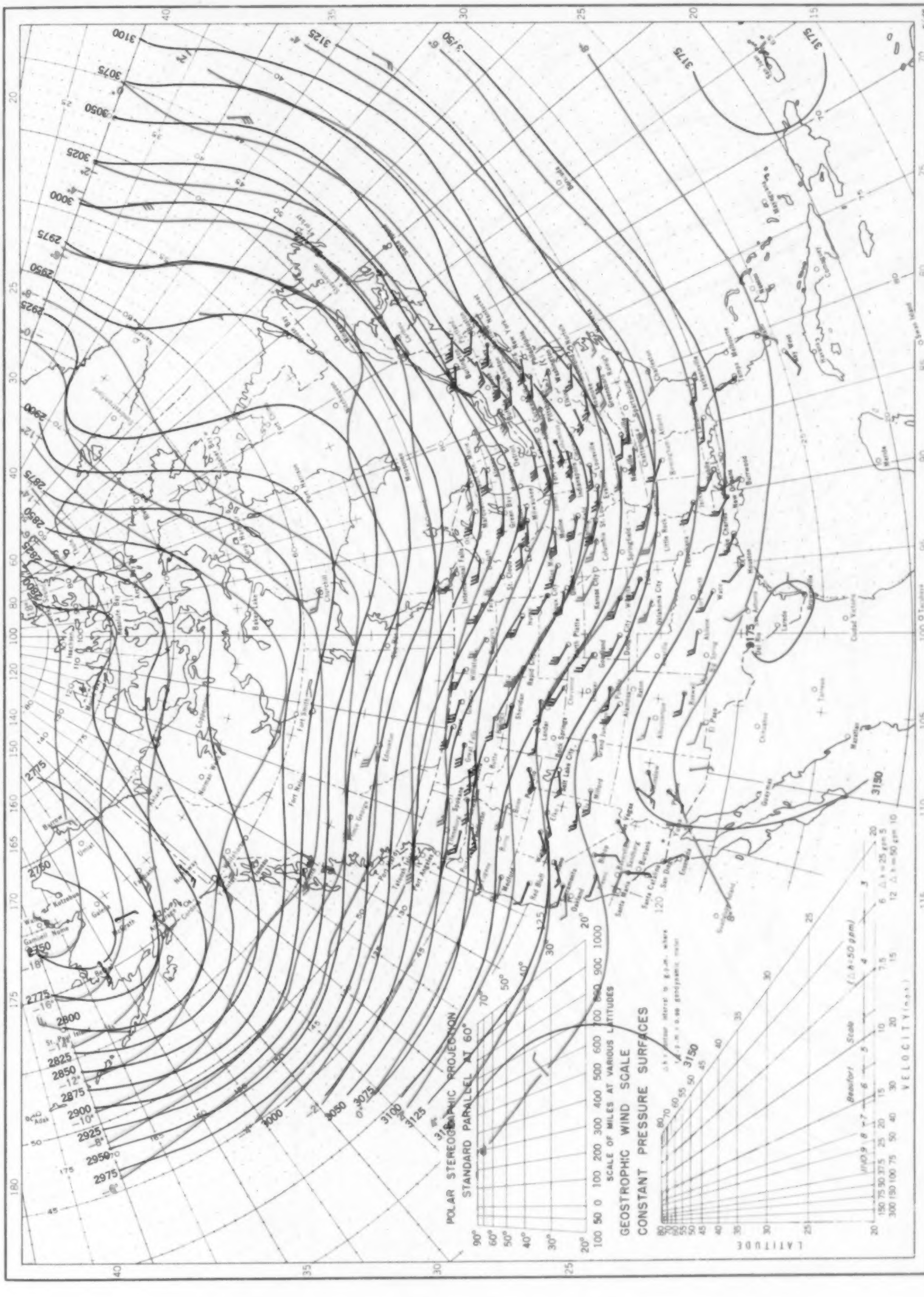
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), October 1955.



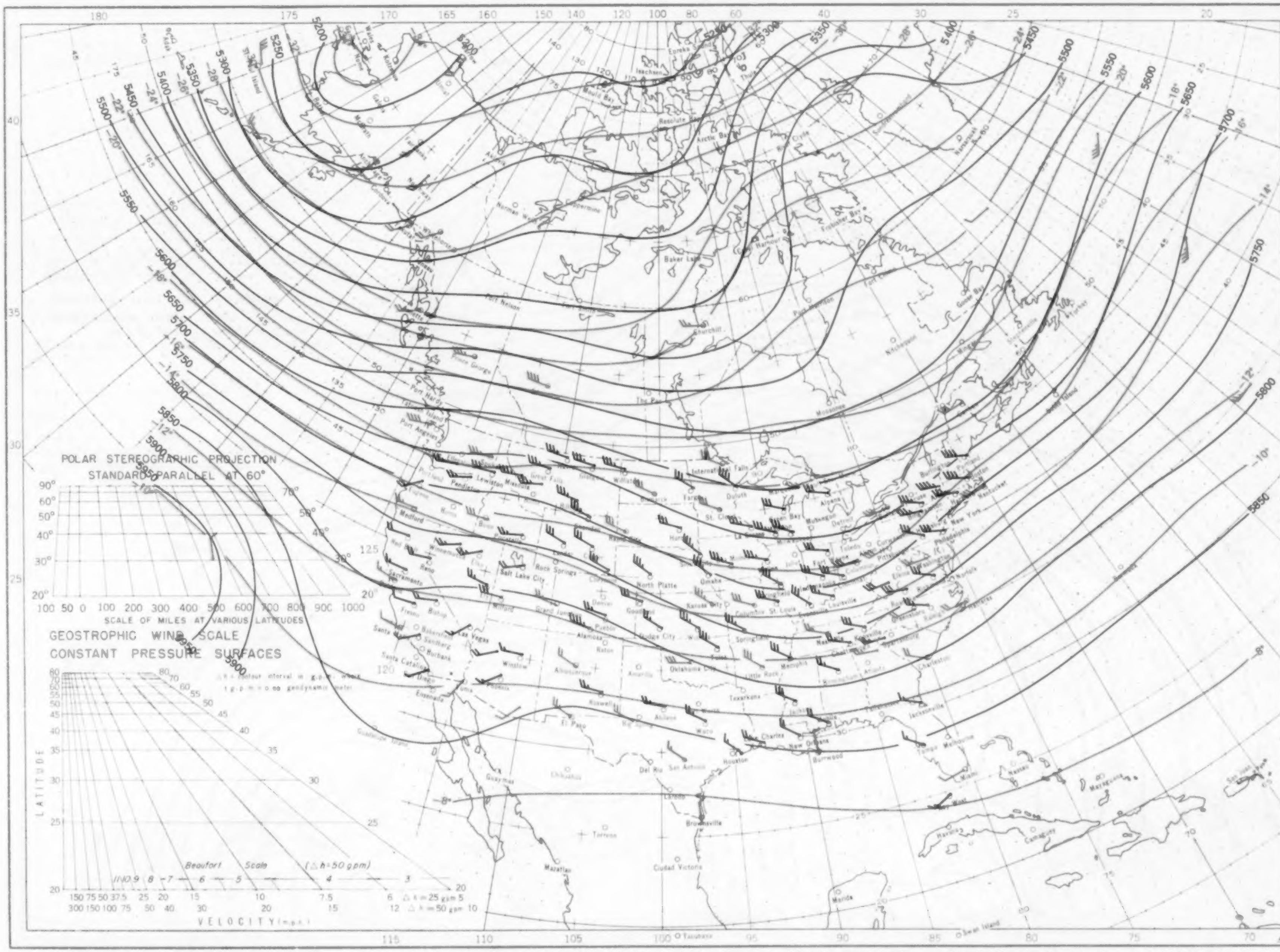
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), October 1955.



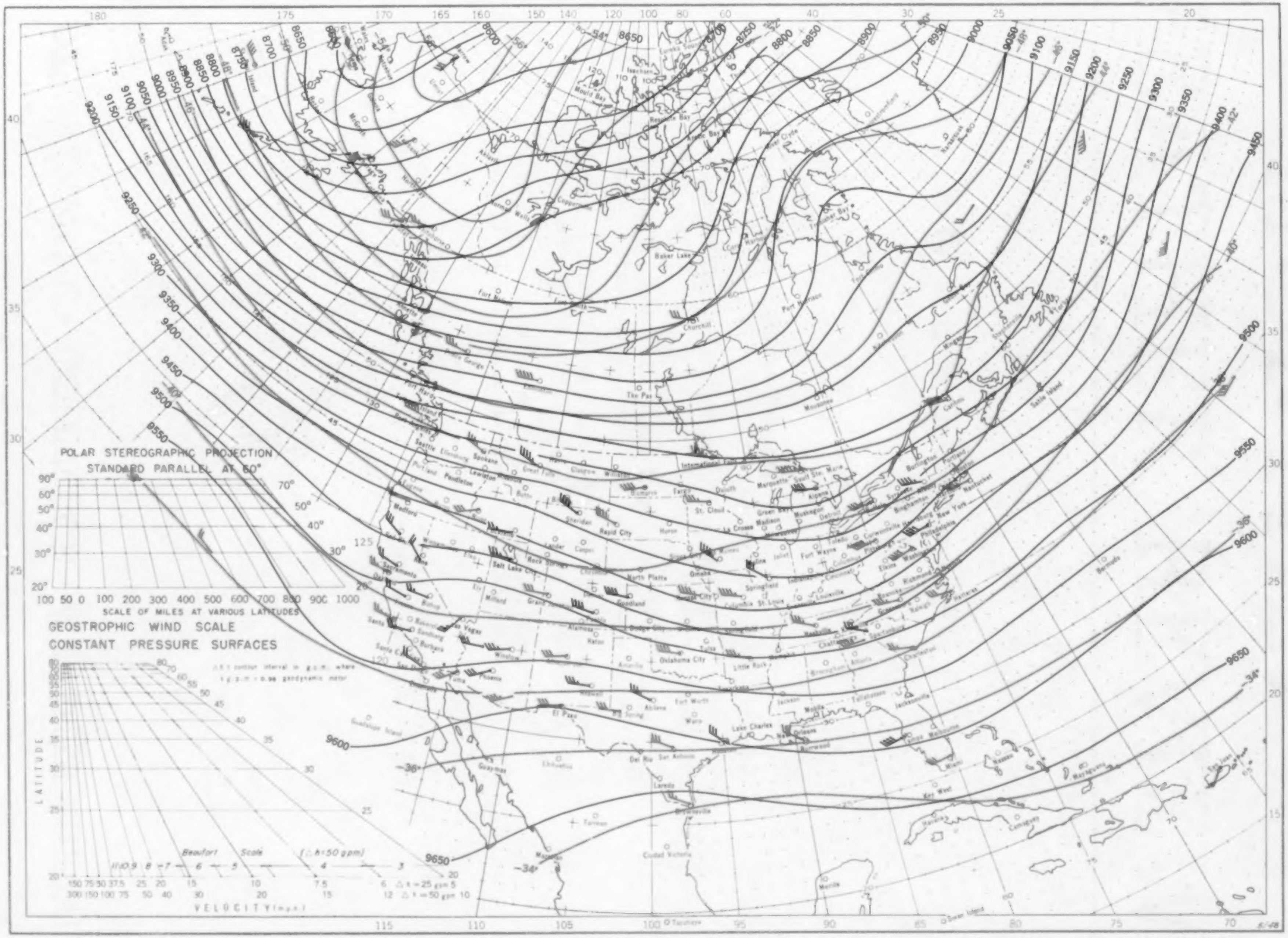
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), October 1955.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), October 1955.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.